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ENVIRONMENTAL ASSESSMENT OF NO_x CONTROL ON A COMPRESSION IGNITION LARGE BORE RECIPROCATING INTERNAL COMBUSTION ENGINE

Volume I
Technical Results

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16. ABSTRACT Volume I of the report gives emission results from field tests of the exhaust gas from a large-bore, compression-ignition reciprocating engine burning diesel fuel. An objective of the tests was to evaluate the operating efficiency of the engine with combustion modification NOx control to reduce emissions to below the proposed NOx new source performance standard (NSPS) of 600 ppm at 15 percent O2 dry. Engine NOx emissions were reduced 31 percent (from 825 to 571 ppm) at 15 percent O2 with 3.5 degrees of fuel injection timing retard. This reduction was accompanied by a 1 percent loss in engine efficiency. CO emissions decreased slightly (from 119 to 90 ppm). Total unburned hydrocarbons remained relatively unchanged (25 ppm), as did particulate emissions (35 ng/J) and total organic emissions (55 ng/J). Volatile organics (boiling point less than about 100 C) accounted for the largest fraction of the total organic. Naphthalene, fluoroanthene, phenanthrene/anthracene, and pyrene were the only organic priority pollutants detected in both tests at levels below 70 micrograms/dscm.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Diesel Engines	Stationary Sources	21G
Combustion Control	Environmental Assessment	14B
Compression Ignition		07B
Assessments	Combustion Modification	
Nitrogen Oxides	Fuel Injection	
Field Tests	Timing Retard	21B
Exhaust Gases		

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SECTION 1

INTRODUCTION

This report describes and presents results for a set of environmental assessment tests performed for the Air and Energy Engineering Research Laboratory/Research Triangle Park (AEERL) under the Combustion Modification Environmental Assessment (CMEA) program, EPA Contract No. 68-02-3188. The CMEA started in 1976 with a 3-year study, the NO_x Control Technology Environmental Assessment (NO_x EA, EPA Contract No. 68-02-2160), having the following objectives:

- Determine multimedia environmental effects of stationary combustion sources and combustion modification technologies
- Develop and document control application guidelines to minimize these effects
- Identify stationary source and combustion modification R&D priorities
- Disseminate program results to intended users

During the first year of the NO_x EA, data and methodologies for the environmental assessment were compiled. Furthermore, priorities for schedule and level of effort to be devoted to evaluating the various source/fuel/control combinations were identified. This effort revealed major data gaps, particularly for noncriteria pollutants (organic emissions and trace elements) for virtually all combinations of stationary combustion

sources and combustion modification techniques. Consequently, a series of seven environmental field test programs was undertaken to fill these data gaps. The results of these tests are documented in seven individual reports (References 1-1 through 1-7) and in the NO_x EA final report summarizing the entire 3-year effort (Reference 1-8).

The current CMEA program has as its major objectives the continuation of multimedia environmental field tests initiated in the original NO_x EA program. These new tests, using standardized Level 1 sampling and analytical procedures (Reference 1-9), are aimed at filling the remaining data gaps and addressing the following priority needs:

- Advanced NO_x controls
- Alternate fuels
- Secondary sources
- EPA program data needs
  - -- Residential oil combustion
  - -- Wood firing in residential, commercial, and industrial sources
  - -- High-interest emissions determination (e.g., listed and candidate hazardous air pollutant species)
- Nonsteady-state operations

New large-bore stationary reciprocating IC engines may become regulated by federal new source performance standards (NSPS) which were proposed on July 23, 1979. These standards require that large-bore compression ignition diesel and dual-fuel engines emit a maximum of 600 ppm NO_x, dry and corrected to 15 percent O_2 and standard atmospheric conditions of 101.3 kPa (29.92 in Hg), 302K (85°F), and 17g moisture/kg dry air (75 grains moisture/lb dry air). The technical feasibility of the proposed NO_x limit is based on

application of combustion modifications available to engine manufacturers (Reference 1-10).

A compression ignition diesel-fired stationary reciprocating IC engine was selected for comprehensive testing under the CMEA program. The objective of the tests was to quantify emissions from the engine under baseline (uncontrolled for NO_x operation) and during controlled operation with combustion modification aimed at meeting the proposed NO_x limit. Prior field tests for multimedia emissions on IC engines using Level 1 procedures have been limited to uncontrolled engine operation (Reference 1-11). The data presented in this report can be used to identify potential environmental effects of combustion modification NO_x controls applied to a large-bore diesel engine, and to identify pollutants of concern.

Concurrent with this test program, a spark-ignited engine burning natural gas was tested to evaluate the effects of the NO_x control on this engine type. Results of this test are documented in a separate report (Reference 1-12). Table 1-1 lists all sources tested to date during the CMEA effort, outlining the combustion modification controls applied and the level of sampling and analysis performed in each case. Results of these test programs are discussed in separate reports.

TABLE 1-1. COMPLETED TESTS DURING THE CURRENT PROGRAM

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Spark ignited natural gas-fired reciprocating internal combustion engine	Large bore, 6-cylinder, opposed piston, 186 kW (250 Bhp)/cyl, 900 rpm, Model 38TDS8-1/8	-- Baseline (pre-NSPS) -- Increased air-fuel ratio aimed at meeting proposed NSPS of 700 ppm corrected to 15 percent O_2 and standard atmospheric conditions	Engine exhaust: -- SASS -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Lube oil	Fairbanks Morse Division of Colt Industries
Compression ignition diesel-fired reciprocating internal combustion engine	Large bore, 6-cylinder opposed piston, 261-kW (350 Bhp)/cyl, 900-rpm, Model 38TDD8-1/8	-- Baseline (pre-NSPS) -- Fuel injection retard aimed at meeting proposed NSPS of 600 ppm corrected to 15 percent O_2 and standard atmospheric conditions	Engine exhaust: -- SASS -- Method 8 -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Lube oil	Fairbanks Morse Division of Colt Industries
Low-NO_x residential condensing heating system furnished by Karlsons Blueburner Systems Ltd. of Canada	Residential hot water heater equipped with M.A.N. low-NO_x burner, 0.55 ml/s (0.5 gal/hr) firing capacity, condensing flue gas	Low-NO_x burner design by M.A.N.	Furnace exhaust: -- SASS -- Method 8 -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Waste water	New test
Rocketdyne/EPA low-NO_x residential forced warm air furnace	Residential warm air furnace with modified high pressure burner and firebox, 0.83 ml/s (0.75 gal/hr) firing capacity	Low-NO_x burner design and integrated furnace system	Furnace exhaust: -- SASS -- Method 8 -- Controlled condensation -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel	New test

TABLE 1-1. (continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Pulverized coal-fired utility boiler, Conesville station	400-MW tangentially fired; new NSPS design aimed at meeting 301 ng/J NO_x limit	ESP inlet and outlet, one test	ESP inlet and outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2 Coal Bottom ash ESP ash	Exxon Research and Engineering (ER&E) conducting corrosion tests
Nova Scotia Technical College industrial boiler	1.14 kg/s steam (9,000 lb/hr) firetube fired with a mixture of coal-oil-water (COW)	-- Baseline (COW) -- Controlled SO_2 emissions with limestone injection	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, CO_2, CO, NO Fuel	Envirocon performed particulate and sulfur emission tests
Adelphi University industrial boiler	1.89 kg/s steam (15,000 lb/hr) hot water firetube fired with a mixture of coal-oil-water (COW)	-- Baseline (COW) -- Controlled SO_2 emissions with Na_2CO_3 injection	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Controlled condensation -- Gas Sample (C_1 - C_6 HC) -- Continuous O_2, CO_2, NO, CO Fuel	Adelphi University
Pittsburgh Energy Technology Center (PETC) industrial boiler	3.03 kg/s steam (24,000 lb/hr) watertube fired with a mixture of coal-oil (COM)	-- Baseline test only with COM	Boiler outlet: -- SASS -- Method 5 -- Controlled condensation -- Continuous O_2, CO_2, NO, TUHC, CO -- N_2O grab sample Fuel	PETC and General Electric (GE)

TABLE 1-1. (continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
TOSCO Refinery vertical crude oil heater	2.54 Ml/day (16,000 bbl/day) natural draft process heater burning oil/refinery gas	-- Baseline -- Staged combustion using air injection lances	Heater outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO, CO, CO_2, HC -- N_2O, grab sample Fuel oil Refinery gas	KVB coordinating the staged combustion operation and continuous emission monitoring
Mohawk-Getty Oil industrial boiler	8.21 kg/s steam (65,000 lb/hr) watertube burning mixture of refinery gas and residual oil	-- Baseline -- Ammonia injection using the noncatalytic Thermal DeNO_x process	Economizer outlet: -- SASS -- Method 5, 17 -- Controlled condensation -- Gas Sample (C_1 - C_6 HC) -- Ammonia emissions -- N_2O grab sample -- Continuous O_2, NO, CO, CO_2 Fuels (refinery gas and residual oil)	New test
Industrial boiler	2.52 kg/s steam (20,000 lb/hr) watertube burning woodwaste	-- Baseline (dry wood) -- Green wood	Boiler outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO, CO Fuel Flyash	North Carolina Department of Natural Resources, EPA IERL-RTP
Industrial boiler	3.16 kg/s steam (29,000 lb/hr) firetube with refractory firebox burning woodwaste	-- Baseline (dry wood)	Outlet of cyclone particulate collector: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO_x, CO Fuel Bottom ash	North Carolina Department of Natural Resources, EPA IERL-RTP

TABLE 1-1. (continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Enhanced oil recovery steam generator	15 MW (50 million Btu/hr) steam generator burning crude oil equipped with MHI low-NO_x burner	-- Performance mapping -- Low NO_x operation	Steamer outlet: -- SASS -- Method 5 -- Method 8 -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO_x, CO, CO_2 -- N_2O grab sample Fuel	Getty Oil Company, CE-Natco
Pittsburgh Energy Technology Center (PETC) industrial boiler	3.03 kg/s steam (24,000 lb/hr) watertube fired with a mixture of coal-water (CWM)	-- Baseline test only with CWM	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO_x, CO, CO_2, TUHC -- N_2O grab sample Fuel Bottom ash Collector hopper ash	PETC and General Electric
Spark-ignited, natural gas fueled internal combustion engine equipped with nonselective NO_x reduction catalyst	610 kW (818 HP) Waukesha engine equipped with DuPont NSCR catalyst	-- Controlled with NSCR -- 15-day emissions monitoring	Catalyst inlet and outlet -- SASS -- NH_3 -- HCN -- N_2O grab sample -- Continuous O_2, CO_2, NO_x, TUHC Fuel	Southern California Gas Company

TABLE 1-1. (concluded)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Industrial boiler	180 kg/hr steam (400 lb/hr) stoker fired with a mixture of coal and waste plastic beverage containers	-- Baseline (coal) -- Coal and plastic waste	Boiler outlet -- SASS -- VOST -- Method 5/8 -- HCl -- Continuous O_2, NO_x, CO, CO_2, TUHC -- N_2O grab sample Fuel Bottom ash Cyclone ash	Vermont Agency of Environmental Conservation
Industrial boiler	7.6 kg/s steam (60,000 lb/hr) watertube retrofit for coal-water slurry firing	-- Baseline test with (CWS) -- 30-day emission monitoring	Boiler outlet -- SASS -- VOST -- Method 5/8 -- Grab sample (C_1-C_6 HC) -- N_2O grab sample -- Continuous NO_x, CO, CO_2, O_2, TUHC, SO_2 Fuel	EPRI, DuPont
Enhanced oil recovery steam generator	15 MW (50 million Btu/hr) steam generator burning crude oil, equipped with the EPA/EER low-NO_x burner	-- Low NO_x (with burner) -- 30-day emission monitoring	Steamer outlet -- SASS -- VOST -- Method 5/8 -- Controlled condensation -- Anderson impactors -- Grab sample (C_1-C_6 HC) -- N_2O grab sample -- Continuous NO_x, CO, CO_2, O_2, SO_2 Fuel	Chevron U.S.A., EERC

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SECTION 2

TEST ENGINE DESCRIPTION

The test program was conducted on a 1570-kW (2100-Bhp), two-stroke, opposed piston, compression ignition, dual-fuel Model 38TDD8-1/8 engine manufactured by the Fairbanks Morse Engine Division of Colt Industries. Figure 2-1 illustrates the piston arrangement of this compression ignition engine which utilizes no cylinder heads or valves. The air-fuel mixture is compressed between the two pistons which work vertically towards each other in each cylinder. The upper and lower pistons drive separate crankshafts interconnected by a vertical drive. The vertical drive connection is made with the lower crankshaft advanced in operating position ahead of the upper crankshaft. This difference in crankshaft positions is called "Lower Crank Lead." A diagram of opposed piston positions in a similar two-cycle spark ignited engine is shown in Figure 2-2. This diagram is similar to the compression ignition engine except for the ignition system which is not aided by an electric spark but is ignited by the heat of compression.

The compression ignition engine as normally marketed by Colt Industries is equipped with a turbocharger. The opposed piston engine used for emissions evaluation on this program utilizes the pulse system of exhaust manifolding to power the turbine-driven turbocharger for improved efficiency. A schematic of the turbo-blower design of the test engine is illustrated in Figure 2-3. The combustion air is drawn into the turbocharger, where it is

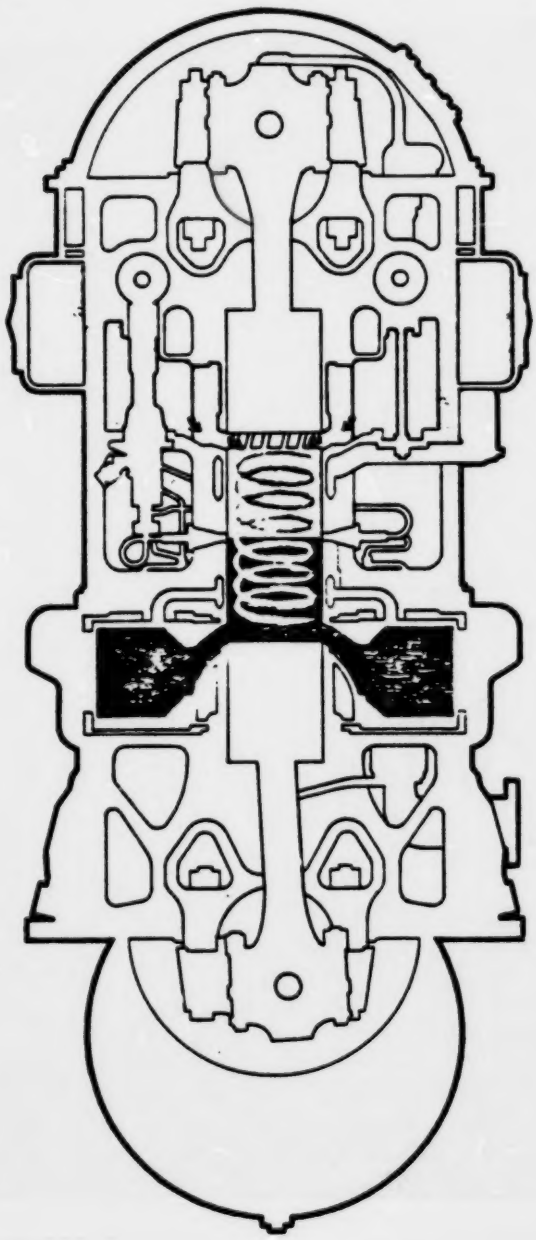


Figure 2-1. Cross section of opposed piston compression ignition engine Model 38TDD8-1/8 (courtesy of the Fairbanks Morse Division of Colt Industries).

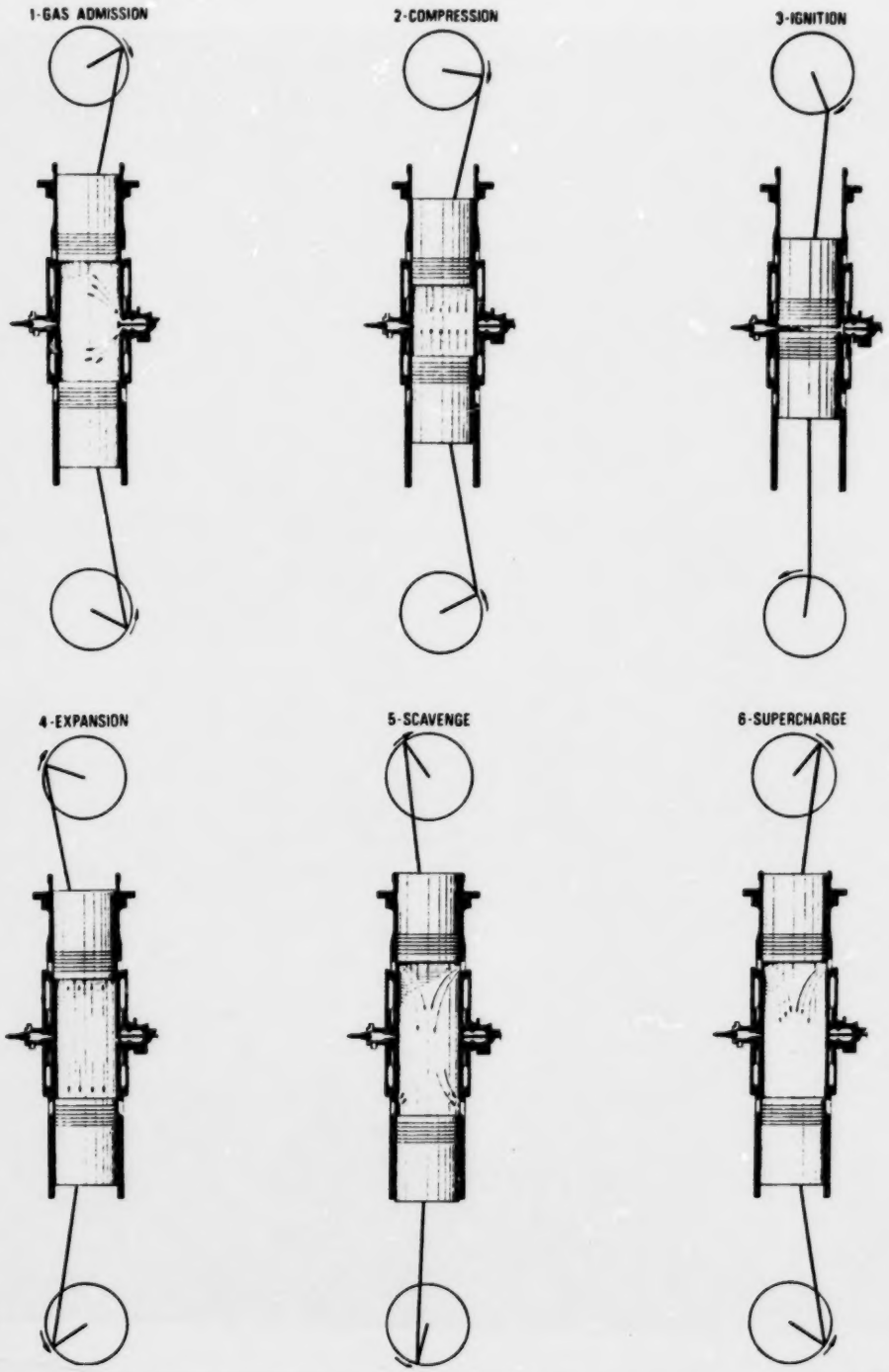
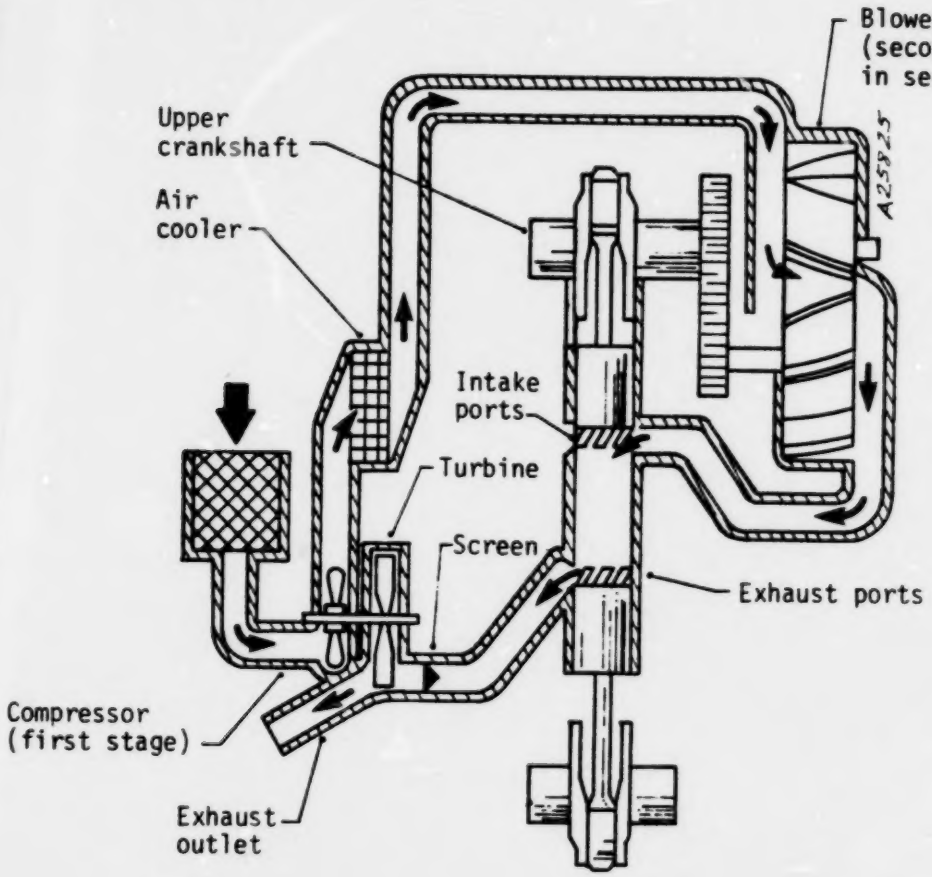


Figure 2-2. Cycle diagram -- opposed piston spark-ignited engine (courtesy of the Fairbanks Morse Division of Colt Industries).



Schematic of turbo-blown arrangement

Figure 2-3. Schematic of the turbo-blower arrangement (courtesy of the Fairbanks Morse Division of Colt Industries).

compressed and discharged through an air cooler to the positive displacement lobe-type blower. The blower is driven by the upper engine crankshaft. The air from the blower is then discharged directly to the cylinders through the engine intake manifold. The inlet air both scavenges the cylinder (sweeping all combustion products from the compression chamber) as well as supplying sufficient charge for the next combustion cycle. Hot exhaust gas leaving from the lower cylinder ports serves to drive the turbine of the turbocharger assembly.

The fuel oil is injected with two high pressure injection nozzles per cylinder. Since this is a dual-fuel (capable of firing mixtures of natural gas and diesel oil) engine design, each cylinder is also equipped with a natural gas injection cell. During dual fuel operation a relatively small amount of pilot fuel oil is used to ignite the natural gas.

Table 2-1 summarizes the design specifications of the engine tested in the program. As indicated, the engine has six cylinders with a displacement of 0.017 m^3 (1037 $in.^3$) per cylinder. The injection timing is normally set at 16 crankshaft degrees before minimum cylinder volume (BMV). The two-stroke engine configuration means that the power cycle is completed in one revolution of the crankshaft as compared with two revolutions for a four-stroke type. In addition to diesel fuel oil, the engine also consumes lubrication oil at a rate of 1 liter per 4.26 GJ (1 gallon per 6000 Bhp-hr). At design operating load of 1565 kW (2100 Bhp) at 900 rpm, lube oil consumption is 0.37 ml/s (0.35 gph) representing approximately 0.09 percent of the total heat supplied to the engine. The remaining 99.91 percent is supplied by the diesel fuel with or without natural gas.

TABLE 2-1. TURBOCHARGED DUAL FUEL COMPRESSION IGNITION ENGINE SPECIFICATIONS

Model Designation	38TDD8-1/8
Serial Number	87247
Configuration	2 Stroke, O.P.
Bore	0.206 m (8-1/8 in.)
Stroke	0.254 m (10 in.) x 2
Number of Cylinders	6
Displacement/Cyl	0.017 m^3 (1037 $in.^3$)
Compression Ratio	11:1
BMEP	1.01 MPa (148.5 psi)
kW/Cylinder (Bhp/Cylinder) @ rpm	261 kW (350 Bhp) at 900 rpm
Hours Since Overhaul	30
Diesel Oil Injection Timing	16° BMV
Lubricating Oil	Mobil 446
L.O. Consumption	4.26 gJ/l (6,000 Bhp-hr/gal)

SECTION 3

NO_x CONTROL AND EMISSIONS RESULTS

Exhaust gas emissions from the diesel-fueled engine were measured during two separate tests: (1) under baseline (uncontrolled for NO_x) operation and (2) with NO_x combustion modification controls (fuel injection retard) applied to reduce NO_x emissions to below the proposed NSPS level of 600 ppm at 15 percent O_2. Section 3.1 summarizes engine operating conditions, describes the combustion modifications applied to reduce NO_x emissions and other test variables, and discusses the impact of control on engine operation. Sections 3.2 through 3.4 summarize emission results by major category of pollutants (i.e., criteria pollutants and other gas phase species in Section 3.2; trace element species in Section 3.3; and organic emissions in Section 3.4). Results of bioassay analyses of the exhaust gas sample organic extract and discussion of the potential environmental impact of NO_x control are summarized in Section 4.

3.1 ENGINE OPERATING PARAMETERS AND TEST VARIABLES

Table 3-1 lists operating parameters of the test engine for the two tests performed. Atmospheric conditions of temperature, humidity, and pressure are also presented as these affect the level of NO_x emitted by the engine.

Engine power output was nearly constant at near maximum rating for the duration of both tests and fuel-air ratio was at normal operating setting.

TABLE 3-1. ENGINE OPERATING PARAMETERS AND AMBIENT ATMOSPHERIC CONDITIONS

Parameter	Baseline	Low-NO_x
Engine Parameters:		
RPM (percent rating)	900 (100%)	900 (100%)
kW_t (Bhp) (percent rating)	1566 (2100) (100%)	1567 (2101) (100%)
kW_e (percent rating)	1503 (99.8%)	1505 (99.8%)
BMEP, MPa (psi)	1.01 (148.5)	1.01 (148.5)
Fuel flow, g/s (lbs/hr)	97.7 (775)	101 (798)
BSFC, g/kW-hr (lbs/Bhp-hr)	225 (0.37)	231 (0.38)
Fuel rate, kW_t in/kW_t out (Btu/Bhp-hr)	2.75 (7009)[a]	2.84 (7218)[a]
Injection timing	16.0° BMV	10.5° BMV
Cylinder firing pressure, MPa (psig)	9.02-9.23 (1320-1350)	8.22-8.34 (1200-1220)
Compressor inlet air temp., K (°F)	305 (89)	291 (65)
Compressor outlet air temp., K (°F)	417 (292)	414 (286)
Blower suction temp., K (°F)	324 (124)	327 (130)
Blower discharge temp., K (°F)	338 (149)	340 (153)
Blower discharge pressure, kPa (psig)	150 (22.0)	176 (25.7)
Air flow, kg/s (lb/min)	4.05 (535)	4.52 (598)
Fuel-air ratio	0.02414	0.02223
Combined cylinder exhaust temp., K (°F)	757 (903)	754 (898)
Turbine exhaust temp., K (°F)	636 (686)	625 (665)
Lube oil consumption, ml/s (gph)	0.37 (0.35)	0.37 (0.35)
Engine efficiency, percent	36.3	35.3
Average Ambient Atmospheric Conditions:		
Ambient temperature - dry bulb, K (°F)	304 (88)	290 (63)
Barometric pressure, kPa (in Hg)	97.3 (28.82)	98.2 (29.07)
Relative humidity, percent	37	45

[a]Accounts for the heating value of lube oil burned by the engine

For the baseline test, fuel injection timing was at the normal setting for this engine. Actual injection timing of diesel engines in the field may vary slightly from the 16° BMV used here depending on engine location and operating conditions.

The combustion modification NO_x control used for the low-NO_x test consisted of retarding the fuel injection timing from 16.0° BMV to 10.5° BMV. The effect of fuel injection retard on NO_x emissions from diesel engines has been widely investigated. The reported level of control is in the range of 0.6 to 8.5 percent reduction for each degree of retard (Reference 3-1).

The primary effect of 5.5° retard on the operation of the test engine was a loss in net efficiency of about 1.0 percent. This efficiency loss is clearly identifiable by the increase in fuel flow needed to maintain rated power output. In order to maintain fuel-air ratio constant, an increase in airflow of nearly 12 percent was also required during the low-NO_x test. Cylinder exhaust temperatures have been reported to increase with retard (Reference 3-1). However, as indicated in Table 3-1, combined cylinder exhaust temperature did not increase in these tests.

Average ambient atmospheric conditions varied significantly between the two tests. During the baseline test, dry bulb temperature averaged 304K (88°F) with 37 percent relative humidity. The low-NO_x test was performed during a much cooler day with ambient dry bulb temperature of 290K (63°F), averaged over a 6-hour test period and slightly higher relative humidity. Both of these ambient condition changes are conducive to reducing NO_x emissions. Specifically, lowered ambient temperature, if translated to lowered air manifold temperature, can result in decreased NO_x emissions

(Reference 3-1). However, for these tests blower discharge temperature remained essentially constant, so no effect of lower ambient temperature on NO_x would have been expected.

Compressor inlet air temperatures reflect ambient conditions. Normally for this laboratory engine, the compressor inlet temperature is maintained at a constant 302K (85°F) which is the standard inlet combustion air temperature at which NO_x emissions are reported. The heat exchanger at the inlet to the turbocharger was malfunctioning during this test program, however, so that compressor inlet temperatures varied according to ambient temperature changes.

3.2 CRITERIA POLLUTANT AND OTHER GAS PHASE SPECIES EMISSION RESULTS

Table 3-2 summarizes criteria pollutant and other gaseous emissions measured during baseline and low-NO_x tests. Emissions of O_2, CO_2, NO/NO_x, CO, and total unburned hydrocarbons (TUHC) were measured continuously and recorded in accordance with the exhaust emission measurement procedures established by the Diesel Engine Manufacturers Association (Reference 3-2). Emissions reported in Table 3-2 represent averages over each 6-hour test period. Sulfur species (SO_2 and SO_3) emissions were measured with EPA Method 8 equipment. Particulate emissions were measured in accordance with EPA Method 5.

Baseline NO_x emissions corrected to 15 percent O_2 and for standard atmospheric conditions averaged 825 ppm (11.0 g/Bhp-hr) or well above the 600 ppm proposed NO_x NSPS. With injection retard NO_x emissions were reduced 30.8 percent on a ppm basis. On a brake-specific basis (g/Bhp-hr), however, emissions were reduced only 28.3 percent, reflecting the efficiency loss of the engine with fuel injection retard.

TABLE 3-2. CRITERIA POLLUTANT AND OTHER GAS SPECIES EMISSIONS

Pollutant	Baseline			Low-NO_x		
As measured by continuous gas analyzers[a]:						
O_2, percent	13.7			14.3		
CO_2, percent	5.3			5.0		
NO, ppm	980			625		
NO_x, ppm	1,015			645		
CO, ppm	145			100		
TUHC, ppm as C_3H_8	32			27		
• Corrected gaseous emissions:	ppm[b]	ng/J[c]	g/Bhp-hr[d]	ppm[b]	ng/J[c]	g/Bhp-hr[d]
NO[e]	797	1,440	10.7	554	1,000	7.64
NO_x[e]	825	1,490	11.0	571	1,040	7.89
CO	119	130	0.96	90	98	0.74
TUHC, as C_3H_8	26	45	0.33	24	42	0.32
By extractive method[a]						
• Sulfur species						
SO_2	18	44	0.33	38	95	0.72
SO_3, as H_2SO_4	4	11	0.08	7	19	0.14
• Particulate mass emissions						
Solid	--	29.5	0.218	--	36.6	0.279
Condensable	--	3.3	0.025	Broken Sample		
Total	--	32.8	0.243	--	36.6	0.279
• Smoke spot						
Bosch No.		0.60			0.65	
Bacharach No.		4.7			5.0	

[a]Appendix A discusses continuous monitoring system, exhaust gas sampling equipment and test procedure used
[b]Corrected to 15 percent O_2, dry
[c]Heat input basis
[d]Shaft output basis
[e]Also corrected for standard atmospheric conditions of 302K (85°F) dry bulb combustion air temperature at inlet of turbocharger and 10.71 g H_2O/kg air (75 grains H_2O/lb air) humidity. Emission rates (ng/J, g/Bhp-hr) as NO_2

Injection of the fuel closer to the top dead-center (TDC) of piston travel or to minimum cylinder volume in the case of the opposed piston engine design, causes the combustion power to extend longer into the power or expansion stroke, possibly causing higher cylinder exhaust gas temperatures which may in turn lead to lower combustible emissions. Although cylinder exhaust gas temperatures did not change significantly during the retard test (see Table 3-1), CO and TUHC emissions showed a slight decrease. This decrease in combustible emissions may also be attributed to a lower fuel-air ratio used during the low-NO_x test. As discussed in the previous section, the increase in fuel oil flow necessary during the low-NO_x test to offset efficiency loss was matched by an increase in combustion air flow resulting in a total reduction of the fuel-air ratio.

Measured SO_2 and SO_3 emissions apparently increased in the low-NO_x test. However, this increase is not considered a result of engine operation or change in sulfur in the fuel oil, but rather due to errors made in carrying out in the Method 8 sampling and analytical procedures. Even though the difference in measured SO_2 emissions suggests a sampling or analytical error, none could be identified upon review of the raw test data. Table 3-3 presents a sulfur balance analysis for both the baseline and low-NO_x tests. The sulfur content of the diesel and lube oils represent average values obtained from triplicate laboratory analyses. As indicated, assuming 100 percent conversion of all the sulfur in the fuel oil combined with a small contribution of the lube oil sulfur, emissions of SO_2 from the engine would be expected to be about 90 ng/J for both tests. Combined SO_2 and SO_3 (as SO_2) emissions measured during the baseline test accounted for only 58 percent of this value, giving a poor sulfur balance. However, combined

TABLE 3-3. SULFUR BALANCE

	Baseline test	Low-NO_x test
Diesel oil sulfur content (percent weight)	0.19	0.20
Lube oil sulfur content (percent weight)	0.96	0.96
Sulfur in diesel and lube oils as SO_2 (ng/J)	88	90
Measured SO_2 (ng/J)	44	95
Measured SO_3, as SO_2 (ng/J)	7	12
Sulfur balance, measured SO_2 + SO_3 as SO_2/ sulfur in diesel and lube oils, as SO_2, percent	58	119
Percent SO_3, of total sulfur oxides emitted (mole basis)	18	16

SO_2 and SO_3 emissions measured for the low-NO_x test are nearly double this value, suggesting that a sampling and/or analytical error was made. Exhaust sulfur emissions were 119 percent of calculated inlet sulfur, a better though still relatively poor sulfur balance.

Overall SO_3 accounted for 16 to 18 percent of the total sulfur oxides leaving the engine. This is a significant fraction compared to the SO_3 fraction typical for external combustion systems.

Solid particulate emissions (the probe and filter catch of the Method 5 train) increased 24 percent for the low-NO_x test. The increase in particulate, or soot, with injection of retard was also evident in the increase in stack opacity measured with smoke spot equipment. The Bosch smoke number increased from 0.60 to 0.65 corresponding to an increase in Bacharach smoke number from 4.7 to 5.0 (see Appendix A for relationship between Bosch and Bacharach smoke numbers). Condensable particulate matter collected (the impinger section catch of the sampling train) accounted for about 10 percent of the total particulate measured for the baseline test. No data are available for condensable matter for the low-NO_x test because the sample collected was broken during shipping from the test site to the laboratory.

Particulate emissions and the particle size distribution measured with the SASS train are summarized in Table 3-4. For comparison the Method 5 results are also noted in the table. Quite good agreement between the two methods is evident.

Particle size distribution data show that particulate matter in the size range of less than 1 μm accounted for over 75 percent of the total particulate for the baseline test and nearly 65 percent for the low-NO_x test.

TABLE 3-4. SUMMARY OF PARTICULATE EMISSIONS AND SIZE DISTRIBUTION

Test	SASS, ng/J[a] (g/Bhp-hr)[b]					Method 5, ng/J[a] (g/Bhp-hr)[b]		
	>10 μm	3-10 μm	1-3 μm	<1 μm (filter)	Total SASS[c]	Solids[c] (probe and filter)	Condensables (impinger catch)	Total method 5
Baseline	5.34 (0.0394)	0.73 (0.0054)	0.05 (0.0004)	20.56 (0.1520)	26.7 (0.1972)	29.5 (0.2181)	3.3 (0.0245)	32.8 (0.2426)
Low-NO_x	14.2 (0.1080)	0.51 (0.0039)	0.02 (0.0001)	26.00 (0.2029)	41.4 (0.3150)	36.6 (0.2787)	--[d]	--

[a]Heat input
[b]Shaft output
[c]SASS oven (solid particulate collection temperature) is 490K (420°F), Method 5 oven is 355K (250°F)
[d]Impinger sample lost during shipping

The increase in particulate emissions for the low-NO_x test was largely attributable to increases in particulate greater than 10 μm.

3.3 TRACE ELEMENT ANALYSIS RESULTS

The lube and diesel fuel oil samples from the engine and the SASS train samples from the engine exhaust were analyzed for 73 trace elements using the Spark Source Mass Spectrometry (SSMS) and Atomic Absorption Spectrometry (AAS). Once the trace element concentrations were determined, trace element flowrates for lube oil, diesel oil and exhaust gas vapor and condensed phases could be computed. Trace element concentrations and flow rates are presented in Appendix B.

Table 3-5 summarizes the calculated trace element flowrates corresponding to lube and diesel oils and exhaust gas samples under baseline and low-NO_x operation for those elements detected in at least one sample. The lube oil flows were calculated based on the lube oil analysis and the engine manufacturer's estimate of lube oil consumption. Only one lube oil sample was taken since this is representative of both baseline and low-NO_x tests. Two diesel fuel oil samples were taken and analyzed separately, one for each test. Both the lube oil and fuel oil represent the total trace element input stream to the engine. Overall, the inorganic trace element flowrates from the lube oil are significantly below those from the diesel oil because of the relative consumption of each. Thus, the contribution of lube oil to trace element emissions for the most part is insignificant.

Trace elements found in the fuel oil at the highest levels (at levels corresponding to flowrates greater than 100 μg/s) were aluminum, calcium, fluorine, iron, magnesium, molybdenum, phosphorus, potassium, silicon, sodium, sulfur, and titanium. Exhaust emissions of many trace elements were

TABLE 3-5. TRACE ELEMENT FLOWRATES

Element	Lube Oil (µg/s)	Diesel Fuel (µg/s)		Engine Exhaust (µg/s)	
		Baseline	Low-NO_x	Baseline	Low-NO_x
Aluminum	0.25	>2,100	500	>2,300	44
Antimony	0.007	--[a]	7.1	0.58	<1.8
Arsenic	0.35	--	--	0.32	0.28
Barium	18	78	30	2.9	68
Beryllium	<0.004	--	--	<0.032	--
Bismuth	--	--	--	<0.032	0.027
Boron	<0.004	2.0	<1.0	36	2.2
Bromine	0.25	39	8.1	15	4.3
Cadmium	0.025	--	--	<6.1	<1.6
Calcium	>35	5,000	1,900	2,300	--
Cerium	--	--	2.0	0.29	--
Cesium	0.004	--	--	<0.32	<0.25
Chlorine	19	68	30	29	--
Chromium	2.4	4.9	10	8.7	47
Cobalt	0.25	7.8	4.0	0.86	25
Copper	1.8	59	20	270	1,500
Fluorine	0.071	20	300	15	230
Gallium	0.018	--	--	1.4	4.7
Germanium	--	--	--	<0.32	<0.28
Iodine	--	<2.9	--	0.064	0.027
Iron	30	980	4.0	870	4,100
Lanthanum	0.011	--	2.0	0.86	--
Lead	0.35	20	30	3.0	33
Lithium	0.025	5.9	4.0	0.26	5.1
Magnesium	1.1	200	100	93	--
Manganese	0.18	20	5.0	23	5.2
Mercury	--	--	--	<290	<0.27
Molybdenum	0.14	200	20	3.0	11
Neodynium	--	--	--	0.86	--
Nickel	0.71	68	40	49	15
Niobium	--	--	--	<0.29	0.51
Phosphorus	2.1	680	50	>2,600	200
Potassium	>35	4,300	5,900	>4,700	>2,700
Rubidium	0.014	--	1.0	2.6	--
Samarium	--	--	--	0.032	0.027
Scandium	<0.007	<2.0	<1.0	29	<0.51
Selenium	0.11	--	--	86	100
Silicon	34	1,500	500	1,200	2,300
Silver	0.004	--	20	37	<7.3
Sodium	>35	98	400	>2,700	>2,400
Strontium	8.1	9.8	20	5.8	7.7
Sulfur	>3,400	190,000	200,000	>4,100	>2,800
Tantalum	--	--	--	--	<8.7
Tellerium	--	--	--	0.16	0.51
Tin	0.071	--	--	20	20
Titanium	2.5	200	200	89	2.5
Tungsten	--	<9.8	--	--	--
Vanadium	0.014	3.9	2.0	0.29	0.25
Yttrium	--	--	--	<0.29	0.25
Zinc	6.3	88	61	280	1,000
Zirconium	--	8.8	--	3.6	1.8

[a]Dashes indicate the concentration of the element was below the detectable limit or the concentration in the sample blank exceeded that of the sample in which case the concentration was set arbitrarily to zero.

one to two orders of magnitude greater than those accountable by the diesel fuel. Elements with highest emitted flowrates (>10^3 µg/s) were aluminum, calcium, copper, iron, phosphorus, potassium, silicon, sodium, sulfur, and zinc.

Emission rates for copper, iron, tin, and zinc (which were generally present in the exhaust at much higher levels than could be accounted for by the fuel and lube oil) may be, in part, caused by engine or exhaust muffler wear, as well as potential contamination of samples during gas sampling, sample recovery and analysis. The contribution of wear of engine internal parts exposed to friction and erosion such as pistons, rings, cylinder liners and the air blower, may be significant sources of metal emissions. Since SASS samples were taken downstream of the engine exhaust muffler, erosion of metal parts in the muffler may have been another significant source for some of the high concentration metals. Potential contamination during sampling are stainless steel parts, vacuum sealants and tubing used in the SASS train. During analysis, Parr bomb ashing of samples prior to SSMS analysis often introduces contamination for a number of elements including iron, copper, nickel, chromium, phosphorus, silicon, cobalt, and platinum.

In a companion test program, trace element emissions were measured in the exhaust gas from a spark-ignited, natural gas-fired engine of similar design to the one tested in this program (Reference 3-3). Results from those tests show trace element emissions on the same order of magnitude as those measured from the diesel engine. The data in Reference 3-3 and the data presented in Table 3-5 seem to indicate that both lube oil and diesel oil can be minor contributors to the inorganic trace element emissions and that engine wear, muffler erosion and potential contamination inherent in the

sampling and analytical procedures may play a significant role in emission levels of these pollutants.

3.4 ORGANIC EMISSION RESULTS

Organic emissions during both the baseline and low-NO_x tests were measured using four methods (see Appendix A for complete method descriptions). Continuous hydrocarbon analyzer (flame ionization detector (FID)) analyses were performed to determine total unburned hydrocarbon (TUHC) emissions. These results were presented in Section 3.2. Volatile organic gas species having boiling points in the C_1 to C_6 range (113K to 363K (-160°F to 90°F)) were determined by onsite analyses of exhaust gas samples by gas chromatography/FID. Semivolatile organic species with boiling points in the C_7 to C_{16} range (363K to 573K (90°F to 572°F)) were determined in the laboratory by total chromatographable organic (TCO) analysis of SASS train sample extracts. SASS train sample extracts were analyzed for total nonvolatile organic species (>C_{16}) having boiling points of greater than 573K (572°F) by gravimetry (GRAV). Further analyses to identify organic functional groups and specify particular organic compounds were performed using infrared spectrometry (IR) and gas chromatography/mass spectrometry. A discussion of the analytical results follows.

3.4.1 TCO and Gravimetric Analyses

Table 3-6 summarizes organic emission results from the TCO and GRAV analyses. The data indicate that the total organic matter (volatile and nonvolatile organics) increased slightly, 1 percent, during low-NO_x operation. While C_1 to C_6 organics decreased about 14 percent with fuel injection retard, nonvolatile organics (>C_{16}) increased over 200 percent. The largest increase in nonvolatile organics was seen in the filter sample.

TABLE 3-6. SUMMARY OF TOTAL ORGANIC EMISSIONS, mg/dscm

Organic Emissions	Baseline test	Low-NO_x test
Volatile organic gases analyzed in the field by gas chromatography:		
C_1	15.7	3.7
C_2	15.6	20.3
C_3	5.1	6.6
C_4	11.4	13.1
C_5	15.3	10.6
C_6	ND	ND
Total C_1 to C_6	63.2	54.2
Volatile organic materials analyzed by TCO procedure:		
Filter	--	--
XAD-2 Cartridge	1.5	1.4
Organic Module Condensate	0.016	0.025
Total C_7 to C_{16}	1.5	1.4
Nonvolatile organic materials analyzed by gravimetric procedure:		
Filter	0.67	10.1
XAD-2 cartridge	4.0	4.4
Organic Module Condensate	<0.12	<0.090
Total >C_{16}	4.6	14.5
Total Organics	69.3	70.1

ND = Not detected.

These data agree reasonably well with total hydrocarbon emission data measured with continuous monitoring equipment, which showed a small decrease in unburned hydrocarbon concentration from 26 to 24 ppm corrected to 15 percent O_2.

Figures 3-1a and 3-1b illustrate organic and particulate emission results in ng/J heat input for the tests in terms of the measurement temperature and the boiling points of the organics. For the baseline test, Figure 3-1a shows that the organic matter in the SASS front half (probe, cyclones, and filter) catch accounts for about 2 percent of the total particulate weight (0.5 ng/J organics out of 25.9 ng/J total weight). The figure also shows that 1.1 ng/J of organic matter was collected in the XAD-2 sorbent and organic module condensate. These additional organics may account, in part, for the slightly higher solid particulate emissions measured with the Method 5 train. Because the Method 5 solid samples are collected at lower temperature (355K (250°F)) than SASS samples (490K (420°F)), it is possible that larger quantities of semivolatile (TCO) organics may have condensed in the front half of the Method 5 train than in corresponding sections of the SASS. Overall, however, front half Method 5 and SASS particulate emissions are in good agreement.

Figure 3-1b illustrates similar results for the low-NO_x test. Here, however, organic matter measured in the SASS front half catch accounts for about 21 percent of the total particulate weight, indicating higher GRAV organic emissions for this test than for the baseline test. Again solid particulate emissions measured with the Method 5 and SASS trains are in good agreement for the low-NO_x test as in the baseline test.

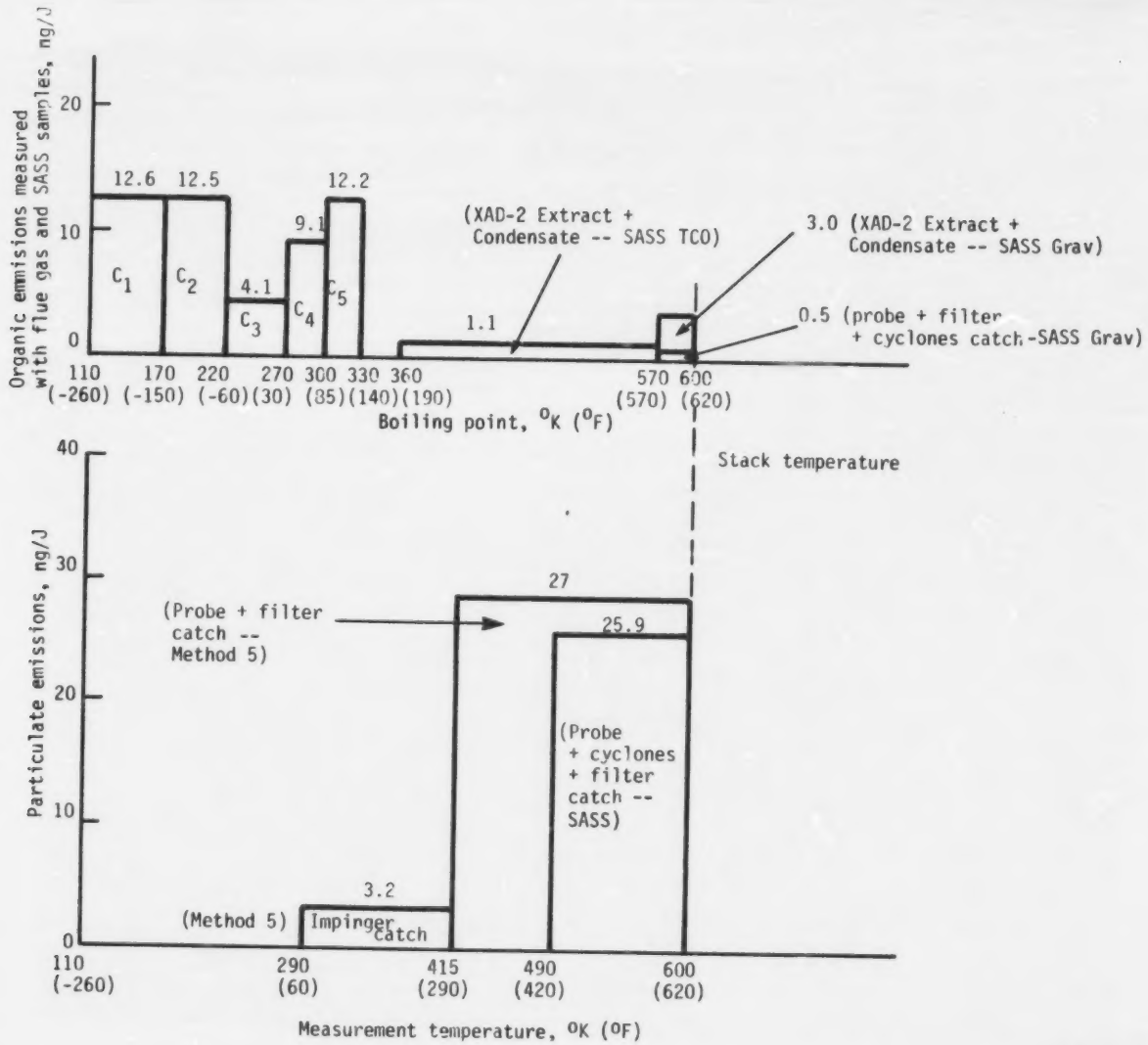


Figure 3-1a. Summary of organic and particulate emissions results (ng/J) -- baseline test.

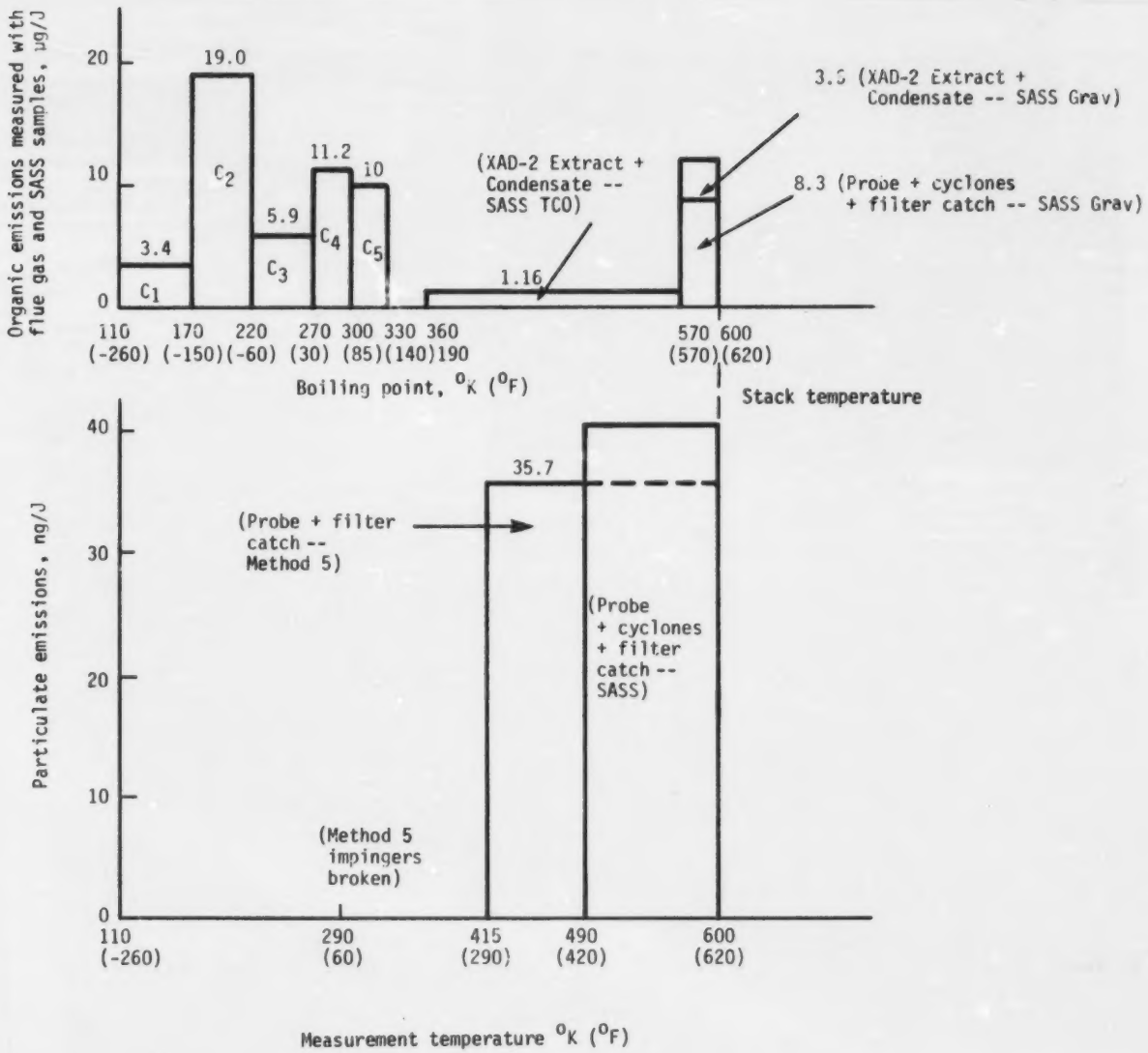


Figure 3-1b. Summary of organic and particulate emissions results (ng/J) -- low-NO_x test.

3.4.2 Infrared Spectra of Total Extracts

IR spectrometry was used to identify organic functional groups present in the gravimetric residue of SASS samples. The results of the IR analyses for the total sample extracts are summarized in Table 3-7. The spectra suggest the presence of aliphatic hydrocarbons as the primary constituents in both filter samples and the organic module condensate extract of the low-NO_x test. They were secondary components in the XAD-2 extracts. Oxygenated hydrocarbons such as carboxylic acids were the primary constituent in the XAD-2 extracts. The spectra for corresponding samples from the two tests were quite similar, although those for low-NO_x test samples were generally stronger. As indicated in Table 3-6, the largest increase in organics with low-NO_x operation was in the particulate (filter) sample during the low-NO_x test.

3.4.3 Gas Chromatography/Mass Spectrometry for POM and Other Organic Compounds

Quantitation of several polycyclic organic matter (POM) compounds and selected other organic species (the semivolatile organic priority pollutant compounds) was performed by GC/MS of SASS train sample extracts. Table 3-8 lists the compounds sought in the GC/MS analyses and their detection limits, and Table 3-9 presents the compounds which were detected and their respective emission levels. As indicated, five compounds were detected in the analysis. Of these, bis(2-ethylhexyl)phthalate is not directly associated with combustion products. Thus, its relatively high concentration level is probably a result of contamination during sampling or laboratory analysis. The compound is a plasticizer and is considered a universal contaminant.

TABLE 3-7. SUMMARY OF INFRARED SPECTRA OF TOTAL SAMPLE EXTRACTS

Sample	Baseline				Low-NO_x			
	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present
Filter probe, cyclone extract	2905	S	CH stretch	Aliphatic hydrocarbons	2905	S	CH stretch	Aliphatic hydrocarbons
	2845	S	CH stretch		2845	S	CH stretch	
					1725	W	C=O stretch	
					1445	W	CH bend	
					1375	W	CH bend	
					725	W	Not assigned	
XAD-2 extract	3575-3070	W	OH stretch	Oxygenated hydrocarbons (carboxylic acids), aliphatic hydrocarbons	3575-3070	W	OH stretch	Oxygenated hydrocarbons (carboxylic acids), aliphatic hydrocarbons
	2505	S	CH stretch		2905	S	CH stretch	
	2845	S	CH stretch		2845	S	CH stretch	
	2750-2450	W	OH		2750-2450	W	OH	
	1725	S	C=O stretch		1725	S	C=O stretch	
	1445	W	CH bend		1445	W	CH bend	
	1265	W	C-O stretch		1265	W	C-O stretch	
	1095	W	C-O stretch		805	W	Not assigned	
	805	W	Not assigned		705	W	Not assigned	
Organic module condensate extract	No peaks	--	--	--	2905	S	CH stretch	Aliphatic hydrocarbons
					2845	S	CH stretch	

[a]S = strong; W = weak

TABLE 3-8. COMPOUNDS SOUGHT IN GC/MS ANALYSIS AND THEIR DETECTION LIMITS (ng/µl INJECTED)

8[a]	4-bromophenyl phenyl ether	40[a]	indeno(1,2,3-cd)pyrene
1[a]	bis(2-chloroisopropyl)ether	2[a]	pyrene
2[a]	bis(2-chloroethoxy)methane	2[a]	acenaphthene
8[a]	hexachlorobutadiene	100[a]	benzidine
40[a]	hexachlorocyclopentadiene	8[a]	1,2,4-trichlorobenzene
1[a]	isophorone	8[a]	hexachlorobenzene
1[a]	naphthalene	8[a]	hexachloroethane
8[a]	nitrobenzene	3[a]	bis(2-chloroethyl)ether
4[a]	N-nitrosodiphenylamine	2[a]	2-chloronaphthalene
40[a]	N-nitrosodi-n-propylamine	4[a]	1,2-dichlorobenzene
3[a]	bis(2-ethylhexyl)phthalate	8[a]	1,3-dichlorobenzene
3[a]	butyl benzyl phthalate	4[a]	1,4-dichlorobenzene
1[a]	di-n-butyl phthalate	20[a]	3,3-dichlorobenzidine
2[a]	di-n-octyl phthalate	10[a]	2,4-dinitrotoluene
2[a]	diethyl phthalate	10[a]	2,6-dinitrotoluene
2[a]	dimethyl phthalate	1[a]	1,2-diphenylhydrazine (as azobenzene)
5[a]	benzo(a)anthracene	2[a]	fluoranthene
7[a]	benzo(a)pyrene	4[a]	4-chlorophenyl phenyl ether
8[a]	3,4-benzofluoranthene	40	anthanthrene
8[a]	benzo(k)fluoranthene	40	benzo(e)pyrene
5[a]	chrysene	--[b]	dibenzo(a,h)pyrene
1[a]	acenaphthylene	--[b]	dibenzo(a,i)pyrene
1[a]	anthracene	40	dibenzo(c,g)carbozole
40[a]	benzo(ghi)perylene	40	7,12 dimethyl benz(a)anthracene
2[a]	fluorene	40	3-methyl cholanthrene
1[a]	phenanthrene	40	perylene
40[a]	dibenz(a,h)anthracene	40	benzo(c)phenanthrene

[a]Authentic standard run
[b]Molecular weight too high for direct analysis by base/neutral run

TABLE 3-9. POM EMISSION SUMMARY

POM Compound	Baseline Test (µg/dscm)				Low-NO_x Test (µg/dscm)			
	Probe, Filter and Cyclones	XAD-2	Organic Module Condensate	Total	Probe, Filter and Cyclones	XAD-2	Organic Module Condensate	Total
Bis ethylhexyl phthalate	32	1100	4.1	1140	83	540	21	644
Fluoranthene	<0.2	24	0.81	25	<1	<1	<0.05	<2
Naphthalene	1.8	67	<0.03	69	<0.5	49	<0.02	49
Phenanthene/Anthracene	0.08	11	0.05	11	<0.5	4	0.05	4.1
Pyrene	<0.2	7	0.3	7.3	<1	<1	<0.05	<2

Known carcinogenic POM compounds such as benzo(a)pyrene, dibenzo(a,h)anthracene, and others were not detected in the analysis. The detection limit of the GC/MS analysis for benzo(a)pyrene, the most carcinogenic of these compounds, was 0.3 µg/dscm.

3.4.4 Liquid Chromatography Separation of Total Sample Extracts

The XAD-2 sample extracts for both tests and the filter (front half) contained more than 15 mg total organic. Thus, these were subjected to liquid chromatography (LC) fractionation. The GRAV and TCO content were then obtained for each LC fraction. Results of these analyses are given in Tables 3-10 through 3-12. For all three extracts most of the organic material was found in the first LC fraction, with the rest being relatively evenly distributed through the other fractions. Fraction 1 generally contains aliphatic hydrocarbons.

TABLE 3-10. TCO AND GRAV RESULTS FOR THE BASELINE TEST XAD-2 EXTRACT LC FRACTIONS

			Total	
Fraction	TCO (mg/dscm)	GRAV (mg/dscm)	(mg/dscm)	(ng/J heat input)
LC1	1.2	1.5	2.7	1.9
LC2	<0.01	<0.1	<0.1	<0.07
LC3	<0.01	0.2	0.2	0.14
LC4	<0.01	0.2	0.2	0.14
LC5	<0.01	0.2	0.2	0.14
LC6	<0.01	0.6	0.6	0.43
LC7	<0.01	0.3	0.3	0.21
Total	1.2	3.0	4.2	3.0

TABLE 3-11. TCO AND GRAV RESULTS FOR THE BASELINE TEST FILTER EXTRACT LC FRACTIONS

Fraction	TCO[a] (mg/dscm)	GRAV (mg/dscm)	Total (mg/dscm)	Total (ng/J heat input)
LC1	--	8.5	8.5	6.2
LC2	--	0.2	0.2	0.1
LC3	--	0.4	0.4	0.3
LC4	--	0.3	0.3	0.2
LC5	--	<0.09	<0.09	<0.07
LC6	--	0.6	0.6	0.4
LC7	--	0.3	0.3	0.2
Total	--	10.3	10.3	7.4

[a]TCO not performed. Sample collected at high temperature

TABLE 3-12. TCO AND GRAV RESULTS FOR THE LOW-NO_x TEST XAD-2 EXTRACT LC FRACTIONS

Fraction	TCO (mg/dscm)	GRAV (mg/dscm)	Total (mg/dscm)	Total (ng/J heat input)
LC1	1.7	2.6	4.3	3.1
LC2	0.03	0.16	0.2	0.1
LC3	0.05	0.35	0.4	0.3
LC4	0.01	0.80	0.8	0.6
LC5	0.005	0.30	0.3	0.2
LC6	0.01	0.50	0.5	0.4
LC7	0.01	0.40	0.4	0.3
Total	1.8	5.1	6.9	5.0

3.4.5 IR Spectra of LC Fractions

The GRAV residues of all sample fractions obtained from LC fractionation of the XAD-2 extracts were subjected to IR analysis. Table 3-13 summarizes the IR spectra results. Only fractions 1 and 5 of the low-NO_x test XAD-2 extract had spectra strong enough to interpret. The presence only of aliphatic hydrocarbons is suggested by the LC1 spectrum. Oxygenated aliphatic species may be indicated by the LC5 spectrum. This is deduced from the indicated presence of such species in the total sample extract. The IR spectra of the LC fractions is consistent with those of the total extracts in that all absorbances in the fractions were present in the total sample. However, a few weak absorbances in the total sample are not accounted for in the fractions.

3.4.6 Low Resolution Mass Spectrometry Analysis of Total Samples Extracts and LC Fractions

Several combined LC fractions of the XAD-2 extracts of both the baseline test and the low-NO_x test and the filter extract of the low-NO_x test, and the total sample filter extract of the baseline test had concentrations of organics corresponding to 0.5 mg/dscm or greater. Thus, they were subjected to low resolution mass spectrometry (LRMS) analysis. Table 3-14 summarizes the results of these analyses.

As shown in the table, the material of significance (LC1 in each extract set and the total filter extract of the baseline test) was indicated to be aliphatic hydrocarbons. A moderate amount of phenolics was seen in LC6+7 of the XAD-2 extract samples in both tests. Carboxylic acids were also seen. The results of batch inlet LRMS were consistent with the direct insertion probe results and with the IR results presented in the previous section.

TABLE 3-13. SUMMARY OF IR SPECTRA OF THE LC FRACTIONS

Fraction	Baseline Test				Low-NO_x Test			
	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present
XAD-2 Extract								
LC1	No peaks	--	--	--	2920	S	CH stretch	Aliphatic hydrocarbon
					2840	S		
					1450	W		
					1270	W	C-O stretch	Alcohols (?)
LC2	No peaks	--	--	--	No peaks	--	--	--
LC3	No peaks	--	--	--	No peaks	--	--	--
LC4	No peaks	--	--	--	No peaks	--	--	--
LC5	No peaks	--	--	--	3620-3140	S	OH stretch	Carboxylic acids, alcohols
LC6	No peaks	--	--	--	No peaks	--	--	--
LC7	No peaks	--	--	--	No peaks	--	--	--
Filter Extract								
LC1	Not fractionated				2920	S	CH stretch	Aliphatic hydrocarbon
					2860	S		
					1470	W		
LC2					No peaks	--	--	--
LC3					2920	S	CH stretch	Aromatic, fused hydrocarbon
					2840	S		
LC4					No peaks	--		
LC5					3520-3420	S	OH stretch	Carboxylic acids, alcohols
LC6					2920	S	CH stretch	
LC7					2920	S	CH stretch	

[a]S = strong; W = weak

TABLE 3-14. SUMMARY OF LRMS ANALYSES

Test/sample	Fraction[a]	Compound category	Intensity[b]
Baseline			
Filter extract	Total extracted	Aliphatic hydrocarbons	1
XAD-2 extract	1	Aliphatic hydrocarbons	100
		Aromatic hydrocarbons	100
		Fused alternate/nonalternate hydrocarbons, MW < 216 (naphthalene plus alkyls)	100
	4+5	Esters	10
	6+7	Phenols	10
		Carboxylic acids	10
		Mercaptans	10
Low NO_x			
Filter extract	1	Aliphatic hydrocarbons	1
	6+7	Phenols	10
		Mercaptans	10
XAD-2 extract	1	Aliphatic hydrocarbons	1
	4+5	Esters	10
	6+7	Phenols	10
		Mercaptans	10

[a]No compound categories identified in sample fractions other than those noted

[b]100 = major component; 10 = minor component; 1 = trace component

Aromatic hydrocarbons and low molecular weight POM's (e.g., naphthalene and alkyl naphthalenes) were found in the baseline test XAD-2 extract LC1. Esters were identified in LC4+5 of both XAD-2 extracts. Phenols and mercaptans were identified in LC6+7 of all extracts. Carboxylic acids were also present in these combined fractions from the baseline test XAD-2 extract.

Mass spectra of corresponding samples were quite similar for both tests.

REFERENCES FOR SECTION 3

3-1. Goodwin, D.R., "Standard Support and Environmental Impact Statement for Stationary Internal Combustion Engines, Volume 1: Proposed Standards of Performance, "EPA-450/2-78-125a, NTIS PB83-113563, July 1979.

3-2. "DEMA Exhaust Emission Measurement Procedure for Low and Medium Speed Internal Combustion Engines," Diesel Engine Manufacturers Association, Cleveland, Ohio, 1974.

3-3. Castaldini, C., "Environmental Assessment of NO_x Control on a Spark-Ignited Stationary Reciprocating Internal Combustion Engine," Acurex Draft Report TR-81-79/EE, April 1984.

3-4. Lentzen, D. E., et al., "IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition)," EPA-600/7-78-201, NTIS PB293795, October 1978.

SECTION 4

ENVIRONMENTAL ASSESSMENT

This section discusses the potential environmental impact of the engine tested and also discusses the results of the bioassay testing of the exhaust gas samples collected from the engine. Exhaust gas stream species concentrations are compared to occupational exposure guidelines to rank species discharged for possible further monitoring or evaluation. Bioassay analyses were conducted as a more direct measure of the potential health and ecological effect of the effluent streams. Both of these analyses are aimed at identifying and providing the basis for ranking pollutant species and discharge streams for further consideration.

4.1 EMISSIONS ASSESSMENT

To obtain a measure of the potential significance of the discharge streams analyzed in this test program, for further monitoring and evaluation, discharge stream concentrations were compared to occupational exposure guidelines, generally either the time-weighted-average Threshold Limit Values (TLV's) defined by the American Conference of Governmental Industrial Hygienists (ACGIH) (Reference 4-1), or the 8-hr time-weighted-average exposure limits established by the Occupational Safety and Health Administration (OSHA) (Reference 4-2).

The comparisons of the exhaust gas stream species concentrations to these occupational exposure guidelines were only performed to rank species emission levels for further monitoring and evaluation.

Table 4-1 lists those pollutant species emitted in the exhaust gas at levels greater than 10 percent of their guideline. As noted in the table, several trace elements were emitted at levels up to eight times their guideline. However, as noted in Section 3.3, trace elements levels measured in the exhaust gas may be attributable to wear of internal parts of the muffler and the engine and to contamination introduced in the sampling/analysis procedures, although confirmation of this is not possible with the available data. For comparison, emissions of the gaseous pollutants CO, SO_2, and SO_3 were at levels ranging from 2 to 20 times their guidelines; NO_x emissions were at levels over 300 times its guidelines. The greater change noted was due to the reduction in NO_x emissions.

4.2 BIOASSAY RESULTS

Bioassay tests were performed on the organic sorbent (XAD-2) extracts. The bioassay tests performed on the XAD-2 extracts were health effects tests only (Reference 4-3). These were:

- Ames assay, based on the property of Salmonella typhimurium mutants to revert due to exposure to various classes of mutagens
- Cytotoxicity assay (CHO) with mammalian cells in culture to measure cellular metabolic impairment and death resulting from exposure to toxicants

A detailed description of the biological analyses for health effects of exhaust gas under baseline and low-NO_x operation is presented in Volume II:

TABLE 4-1. EXHAUST GAS POLLUTANTS EMITTED AT CONCENTRATIONS GREATER THAN 10 PERCENT OF THEIR OCCUPATIONAL EXPOSURE GUIDELINE

Pollutant	Exhaust Gas Concentration (mg/dscm)		Occupational exposure guideline (mg/m^3)[a]
	Baseline	Low-NO_x	
NO_x (as NO_2)	1940	1230	6.0
SO_2	57	113	5.0
SO_3	14	23	1.0
CO	170	117	55
Phosphorus, P	>0.79	0.054	0.10
Copper, Cu	0.081	0.40	0.10[b]
Iron, Fe	0.26	1.1	1.0
Silver, Ag	0.011	<0.0020	0.010
Potassium, K	>1.4	>0.72	2.0[c]
Sodium, Na	>0.82	>0.65	2.0[c]
Calcium, Ca	>0.70	--	2.0
Aluminum, Al	0.69	0.012	2.0
Zinc, Zn	0.085	0.27	1.0
Chromium, Cr	0.0026	0.012	0.050
Lead, Pb	0.0009	0.0087	0.050[b]
Nickel, Ni	0.015	0.0041	0.10
Selenium, Se	0.026	0.027	0.20

[a]Time-weighted-average TLV (Reference 4-1) unless noted
[b]8-hr time-weighted-average OSHA exposure limit
[c]Ceiling limit

Data Supplement. The results of these assays are summarized in Table 4-2 for the exhaust gas samples (organic sorbent module extract) for both baseline and low-NO_x tests. These results suggest that the exhaust gas, under both baseline and low-NO_x operation, is of moderate to high toxicity and moderate mutagenicity.

4.3 SUMMARY

A compression ignition large bore reciprocating IC engine was tested under baseline (uncontrolled) operation, with fuel injection retard to control NO_x emissions to below the proposed NSPS of 600 ppm (at 15 percent O_2). Accordingly, NO_x emissions were decreased 31 percent from 825 to 571 ppm at 15 percent O_2. With retard, engine efficiency was decreased from 36.3 to 35.3 percent. CO emissions decreased slightly, from 119 to 90 ppm at 15 percent O_2. Total unburned hydrocarbon, as measured by a continuous hydrocarbon analyzer, remained relatively constant at about 25 ppm (as propane) at 15 percent O_2, as did particulate emissions at about 35 ng/J heat input. Total organic emissions also remained relatively unchanged, at about

TABLE 4-2. BIOASSAY RESULTS

		Evaluation	
Sample	Test	CHO[a]	Ames[b]
XAD-2 extract	Baseline	H	M
XAD-2 extract	Low-NO_x	H/M	M

[a]H = high toxicity; M = moderate toxicity
[b]H = high mutagenicity; M = moderate mutagenicity

55 ng/J. Volatile organics (nominally C_1 to C_6 hydrocarbons) accounted for the largest fraction of the total organic emissions.

Aliphatic hydrocarbons were the predominant category in the semivolatile and nonvolatile fractions (nominally C_{7+}) of the organics analyzed. However, the presence of esters, phenols and mercaptans was apparent in both test samples. The presence of aromatic hydrocarbons was apparent in the baseline samples.

Of the 58 semivolatile organic priority pollutant species analyzed, only naphthalene, fluoranthene, phenanthrene/anthracene, and pyrene were detected in the baseline test exhaust gas at levels of 7 to 70 µg/dscm. Levels of these in the low-NO_x test exhaust gas were lower, being <1 to 50 µg/dscm.

REFERENCES FOR SECTION 4

4-1. "Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment With Intended Changes for 1983-84," American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1983.

4-2. OSHA Safety and Health Standards, 29 CFR Part 1910, Subpart Z.

4-3. Brusick, D. J., and R. R. Young, "IERL-RTP Procedures Manual: Level 1 Environmental Assessment, Biological Tests," EPA-600/8-81-024, NTIS PB228966, October 1981.

APPENDIX A

SAMPLING AND ANALYSIS METHODS

Emission test equipment was provided by Acurex Corporation and Colt Industries. Continuous monitoring analyses for criteria pollutants and other gas phase species emissions were provided by Colt Industries. The gas monitoring system is used by the engineering personnal of Colt Industries in studying NO_x controls for reciprocating internal combustion engines and monitoring their effects. Onsite equipment provided by Acurex Corporation included particulate and sulfur analysis trains (EPA Method 5 and Method 8 specified equipment), the SASS train and a gas chromatograph analyzer for volatile hydrocarbon analysis. A laboratory area was provided by Colt Industries for equipment preparation, sample recovery and preliminary onsite sample analysis.

The following sections briefly describe the equipment and sampling procedures used during Level 1 source evaluation and assessment of NO_x control for the reciprocating internal combustion engine at the Fairbanks Morse Division of Colt Industries.

A.1 CONTINUOUS MONITORING SYSTEM FOR GASEOUS EMISSIONS

The continuous monitoring system for gaseous emissions conformed to the Diesel Engine Manufacturers Association (DEMA) exhaust emission measurement procedure (Reference A-1). The list of analytical equipment and calibration gases used is presented in Table A-1. The exhaust gas

TABLE A-1. LIST OF CONTINUOUS MONITORING ANALYZERS AND CALIBRATION GASES USED

Continuous Monitors:

Species	Manufacturer	Measurement Method	Model No.
CO_2/CO	Infrared Industries, Inc. Santa Barbara, California	IR Spectrometer	702
O_2	Serbomax (Scott Corp)	Paramagnetic	150
$NO-NO_x$	Thermo Electron Co.	Chemiluminescent	10A
CH_4/UHC	Scott Corporation	Flame Ionization	215
Smoke	Bosch - W. Germany	Light transmissometer	EFAW 68A

Calibration Gases:

Species	Manufacturer	Concentration[a]	Age
CO/CO_2	Air Co. Specialty Gases	409 ppm CO 5.21% CO_2	2 months
NO/NO_2	Air Co. Specialty Gases	967 ppm NO <8 ppm NO_2	2 months
C_3H_8	Air Co. Specialty Gases	29 ppm and 765 ppm	2 months
O_2	Air Co. Specialty Gases	2.0%	2 months

[a]Balance N_2

sample was taken upstream of the engine exhaust muffler and the heat exchanger which served to control combustion air inlet temperature. A heated sample line, equipped with two filters (one inside the exhaust duct and one outside) was used to draw the gas to the total hydrocarbon emission

monitoring system. An unheated sample line, connected to the heated line upstream of the hydrocarbon analyzer, served the remaining instruments in the continuous monitoring system.

A Bosch smoke emission analyzer was also used in the test program. This instrument remained in service throughout the test. Figure A-1 illustrates the relationship between the Bosch-0.3 liter and the Bacharach smoke readings. The Bosch smokemeter is used widely among engine manufacturers.

A.2 PARTICULATE TESTS

Particulate mass tests were conducted in accordance with EPA Methods 1 through 5. The following sampling equipment was used:

- A 316 stainless steel sampling nozzle properly sized for isokinetic sampling
- Stainless steel-lined sampling probe equipped with a thermocouple to measure probe temperature, a thermocouple to measure stack gas temperature, and a calibrated S-type pitot tube to measure velocity pressure
- A teflon-coated stainless steel 142 mm (5.59 inches) filter holder
- An impinger train containing four glass bottles to collect moisture and condensable material escaping the filter
- A 4.7×10^{-3} m^3/s (10-cfm) carbon vane pump modified for very low leakage around the shaft
- A control module to monitor temperature, pressure, and flowrate throughout the sampling train

Sampling Probe

A 1.52 m (5-ft) heated stainless steel-lined probe was used to isokinetically extract samples from the stack. The probe has a closed loop

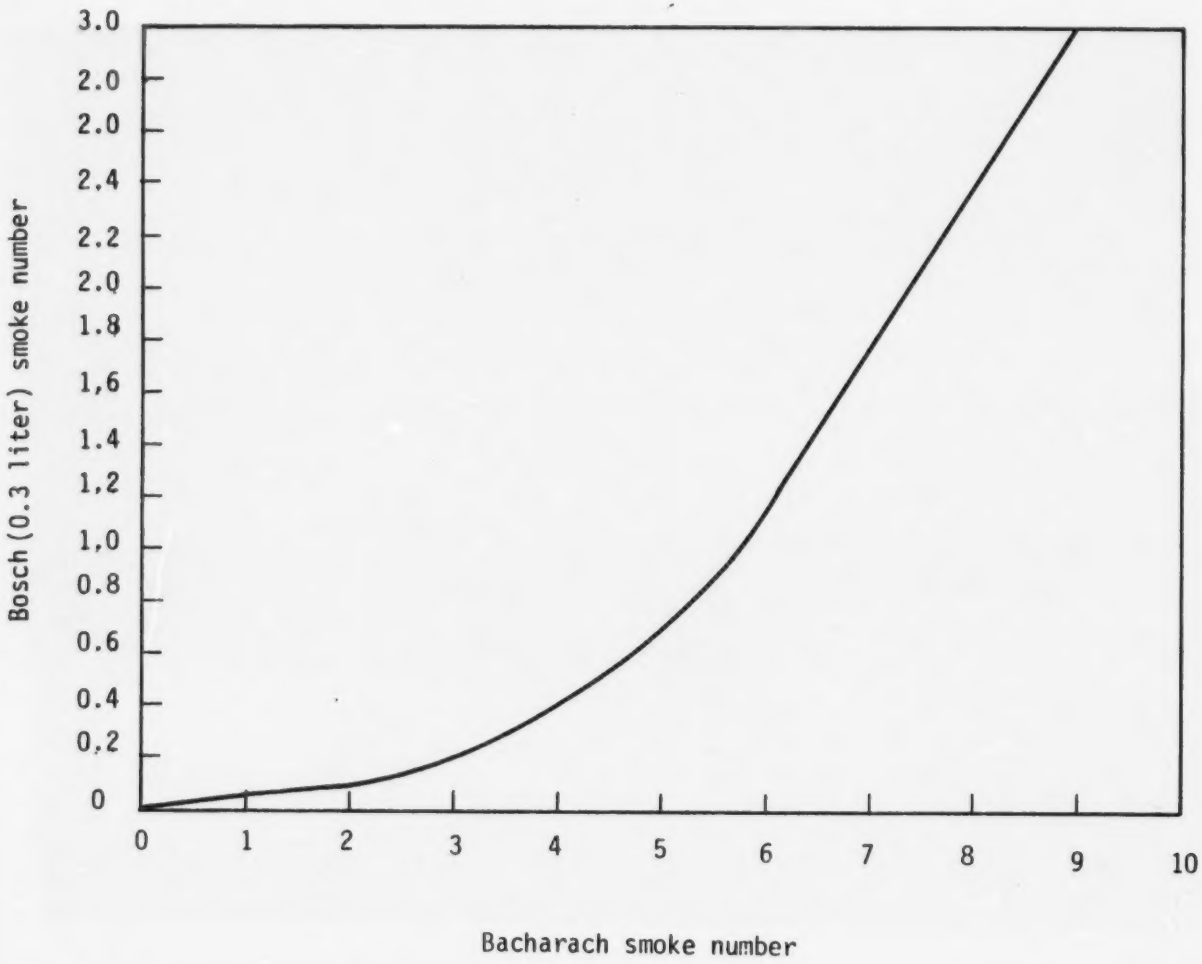


Figure A-1. Relation of Bosch to Bacharach smoke number.

temperature control system to keep the probe at 394K (250°F) as required by EPA Method 5. The probe is equipped with an S-type pitot tube to measure stack gas velocity pressure and a thermocouple to measure stack gas temperature.

Filter Holder

For the particulate mass tests, a 316 stainless steel, teflon-coated 142-mm (5.59-in.) filter holder containing a glass fiber filter was used to capture the particulates.

Impinger Train

The impinger train for the particulate mass tests was immersed in an icebath and consisted of four glass impinger bottles equipped with teflon caps and 316 stainless steel stems, connector tubes, and fittings. The first two bottles contained 400 ml of distilled water, the third bottle was empty, and the fourth contained a known amount of silica gel.

Control Module

The control module monitors temperatures, pressures, and flowrates throughout the sampling train. For these tests, the orifice ΔH is indicated on a 0-1.5 kPa (0 to 6 in. H_2O) magnehelic gauge where the smallest division is 25 Pa (0.1 in. H_2O). The velocity pressure of the stack gases is indicated on a 0 to 124 Pa (0 to 0.5 in. H_2O) or a 0 to 1 kPa (0 to 4 in. H_2O) magnehelic gauge.

The control module contains a Rockwell Model 415 dry gas meter to measure the total volume of gas sampled to the nearest 1.4×10^{-4} m^3 (0.005 ft^3). An orifice meter (after the dry gas meter) is used to measure the instantaneous flowrate through the sampling train to ensure sampling is done isokinetically.

Finally, the control module has an eight-position thermocouple switch to measure temperatures throughout the sampling train. Figure A-2 illustrates all these components of the Acurex High Volume Stack Sampler used for conducting the test program.

A.2.1 Sample Collection

Sample collection took place in the uninsulated stack above the engine exhaust muffler. For each test, clean filters were placed in the sealed filter holder in the cleanup laboratory and the train was then transported to the stack for use. Once on the stack the sample train was assembled. Leak checks were performed before and after each test and as necessary during the test. Upon completion of the test, the probe and nozzle were cleaned and the impinger solution volumes were measured and recorded. The filter holder was sealed and brought to the cleanup laboratory for reclaiming.

The particulate tests were performed at 36 sample points in accordance with EPA Method 1. These test points are illustrated in Figure A-3. Each point was sampled for 5 minutes, hence a 180-minute total sample time.

A.2.2 Sample Recovery

Figure A-4 illustrates the Method 5 sample recovery utilized to measure total particulate mass collected with the HVSS train. Solid particulate matter is defined as all particulate mass collected in the front half of the train; that is the filter, the probe and the nozzle. Condensible particulate matter is obtained from gravimetric analyses of impinger liquids and impinger rinses. The impinger solutions are treated with ethyl ether to separate the organic matter from the liquid and solid samples.

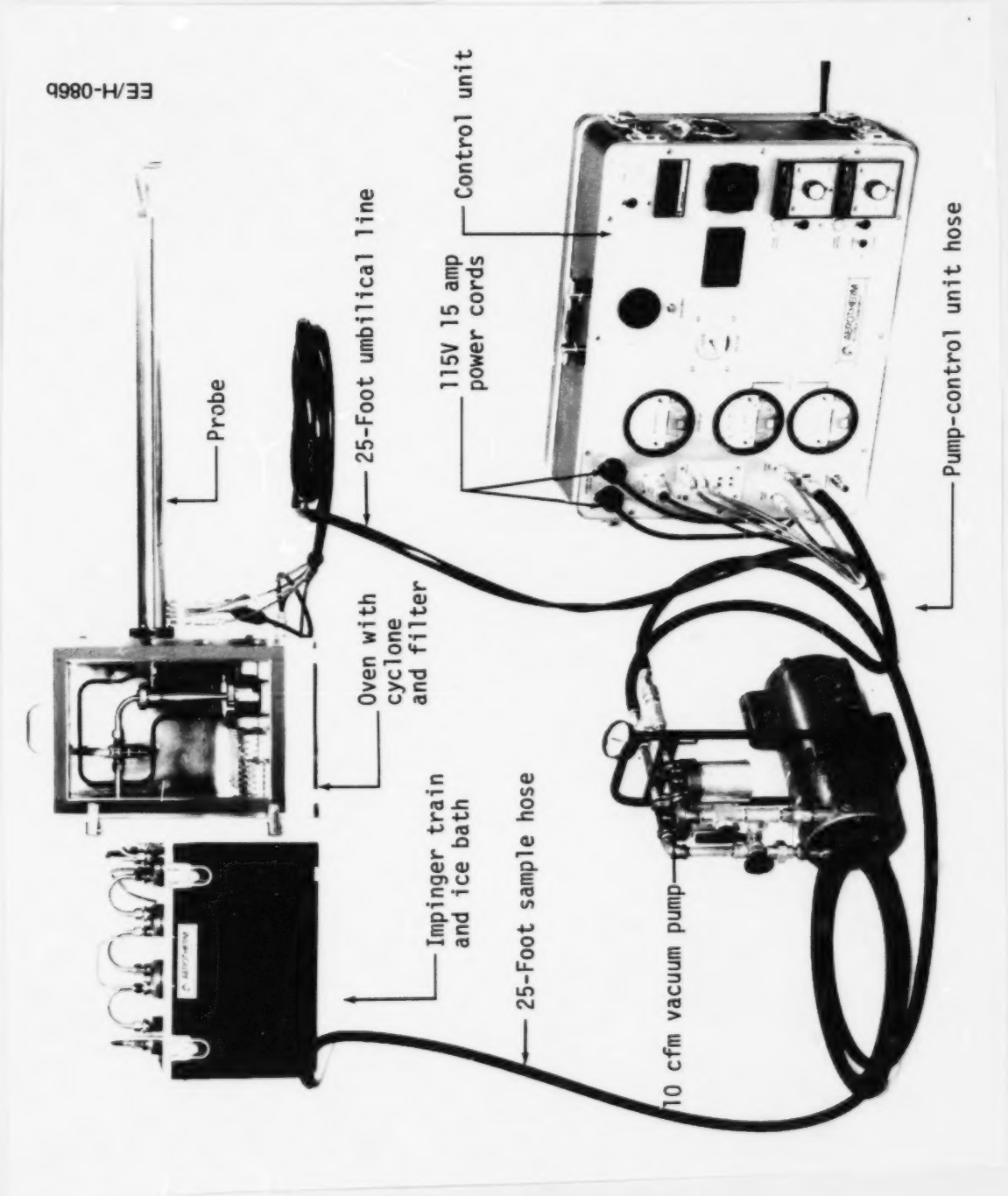
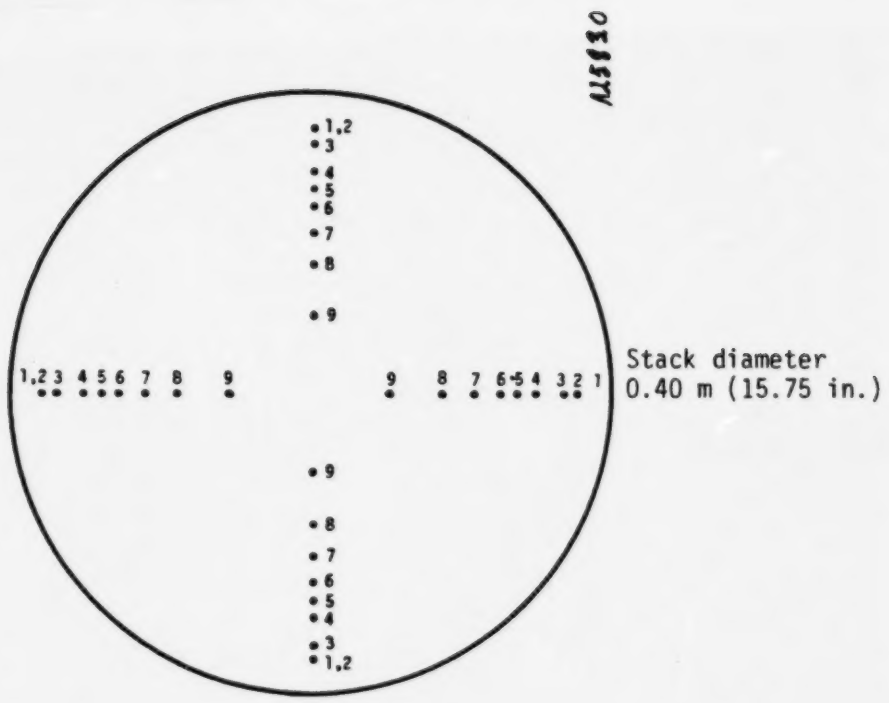


Figure A-2. Acurex high volume stack sampler.



Location from the duct wall, m (in.)

Point		
1	0.025	(1.0)
2	0.025	(1.0)
3	0.030	(1.18)
4	0.044	(1.71)
5	0.058	(2.30)
6	0.075	(2.96)
7	0.094	(3.72)
8	0.118	(4.66)
9	0.153	(6.02)

Figure A-3. Particulate sampling point locations for compression ignition engine.

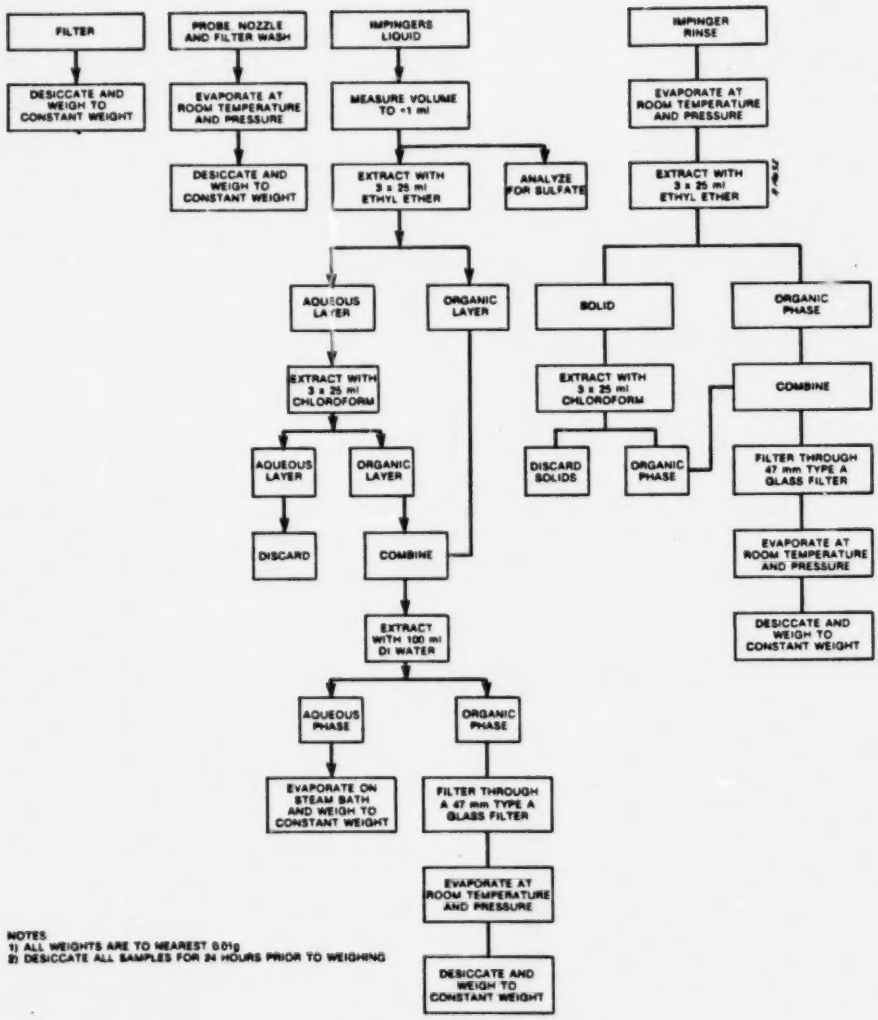

FILTER
PROBE, NOZZLE AND FILTER WASH
IMPINGERS LIQUID
IMPINGER RINSE
DESICCATE AND WEIGH TO CONSTANT WEIGHT
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
MEASURE VOLUME TO ±1 ml
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
DESICCATE AND WEIGH TO CONSTANT WEIGHT
EXTRACT WITH 3 x 25 ml ETHYL ETHER
ANALYZE FOR SULFATE
EXTRACT WITH 3 x 25 ml ETHYL ETHER
AQUEOUS LAYER
ORGANIC LAYER
SOLID
ORGANIC PHASE
EXTRACT WITH 3 x 25 ml CHLOROFORM
EXTRACT WITH 3 x 25 ml CHLOROFORM
COMBINE
AQUEOUS LAYER
ORGANIC LAYER
DISCARD SOLIDS
ORGANIC PHASE
FILTER THROUGH 47 mm TYPE A GLASS FILTER
DISCARD
COMBINE
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
EXTRACT WITH 100 ml DI WATER
DESICCATE AND WEIGH TO CONSTANT WEIGHT
AQUEOUS PHASE
ORGANIC PHASE
EVAPORATE ON STEAM BATH AND WEIGH TO CONSTANT WEIGHT
FILTER THROUGH A 47 mm TYPE A GLASS FILTER
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
DESICCATE AND WEIGH TO CONSTANT WEIGHT
NOTES
1) ALL WEIGHTS ARE TO NEAREST 0.01g
2) DESICCATE ALL SAMPLES FOR 24 HOURS PRIOR TO WEIGHING

Figure A-4. Sample analysis scheme for particulate sampling train.

A.3 SULFUR EMISSIONS

SO_2 and SO_3 emissions were measured using a modified HVSS sampler in accordance with EPA Method 8 procedures. In this procedure, a gas sample is extracted from a single point in the stack. In the impinger train for this method the first bottle contains isopropanol and the second contains hydrogen peroxide. A filter is placed between the two impinger bottles. Sulfuric acid mist and any vapor phase SO_3 is trapped in the isopropanol impinger. The back up filter traps any carryover mist. SO_2 is absorbed in the H_2O_2 impinger.

After completion of a test the filter is rinsed with isopropanol; the rinse solution is added to the isopropanol impinger solution. Absorbed SO_3 and H_2SO_4 in the isopropanol and SO_2 in the H_2O_2 are determined separately by barium-thorin titration.

A.4 TRACE ELEMENTS AND ORGANIC EMISSIONS

Emissions of inorganic trace elements and organic compounds were sampled with the SASS. Designed and built for EPA's Process Measurement Branch for Level 1 environmental assessment, the SASS collects large quantities of gas and solid samples required for subsequent analyses of inorganic and organic emissions as well as particle size measurement.

The SASS system, illustrated in Figure A-5, is similar to the HVSS system utilized for total particulate mass emission tests described in the previous section with the exception of:

- Particulate cyclones heated in the oven with the filter to 500K (450°F)
- The addition of a gas cooler and organic sampling module
- The addition of necessary vacuum pumps

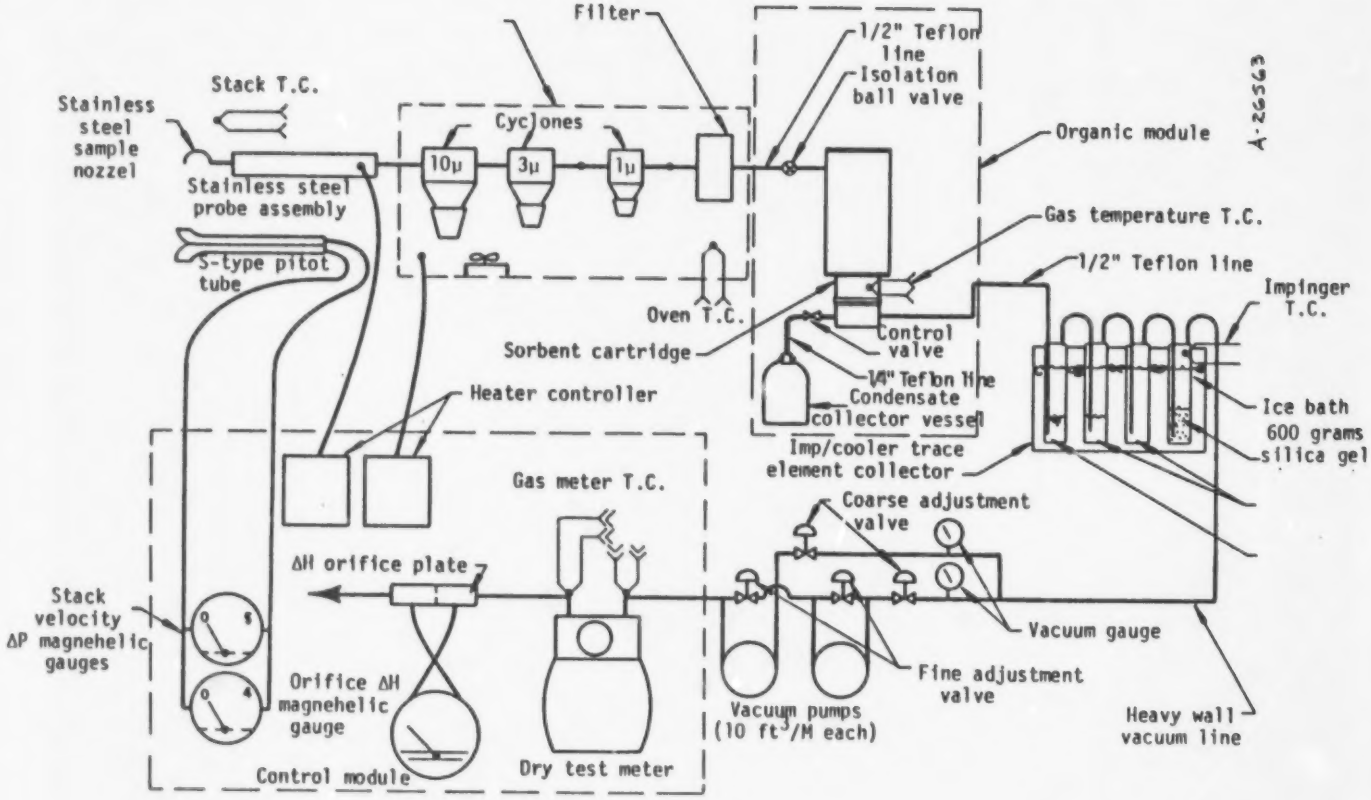


Figure A-5. Source assessment sampling system schematic.

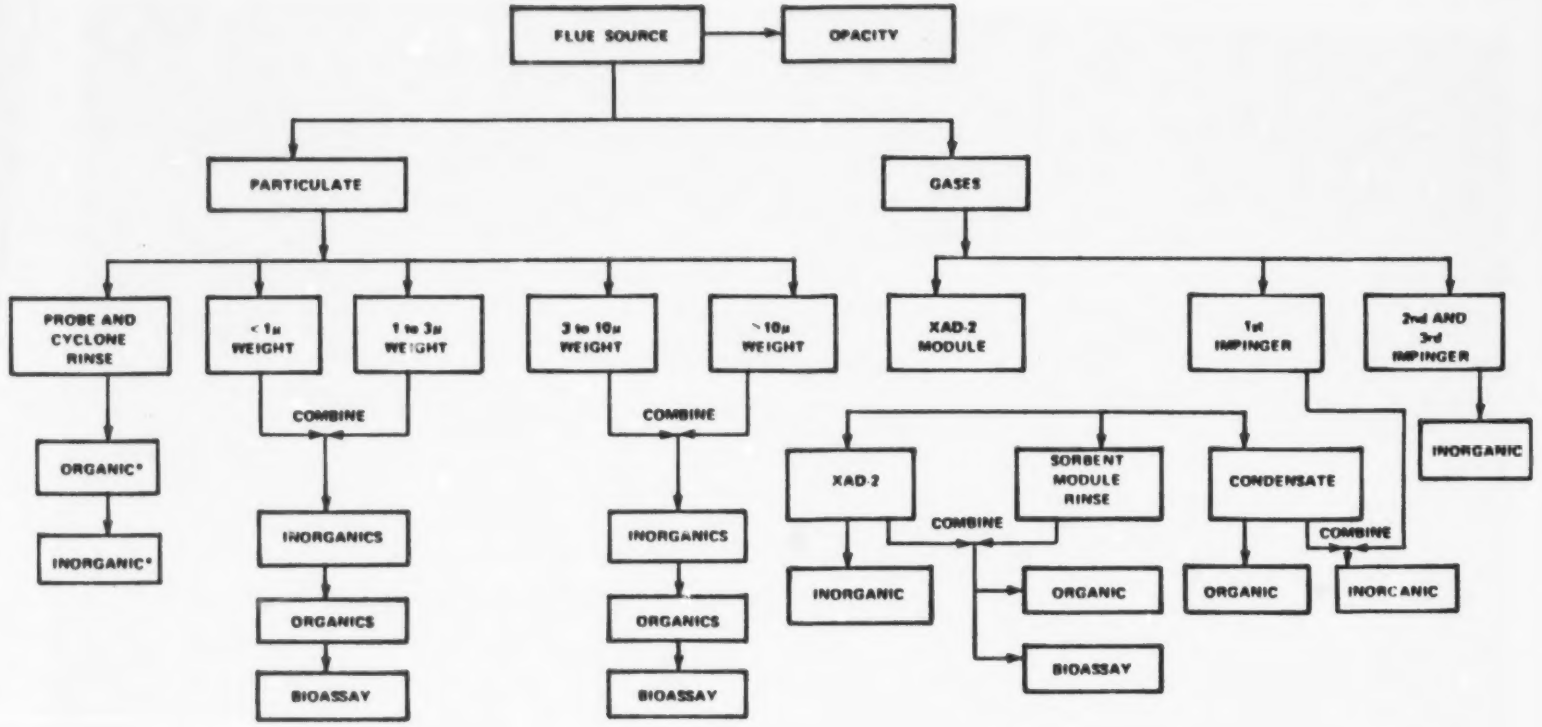
Schematics outlining the sampling and analytical procedures using the SASS equipment are presented in Figures A-6 and A-7. Since the total particulate catch from this source was so small, the probe rinse, cyclones, and filter catches were combined to form one particulate sample for analysis.

Inorganic analyses of solid and liquid samples from the SASS train and fuels were performed with SSMS for most of the trace elements. AAS was used for analyses of mercury (Hg), antimony (Sb), and arsenic (As). Quantitative information on total organic emissions was obtained by TCO analyses and by gravimetry (GRAV) of methylene chloride extracts of SASS samples. GC/MS was used for POM and selected other organic species (the semivolatile organic priority pollutants) analyses of solid and liquid extract SASS samples. Figure A-8 illustrates the organic analysis methodology followed during the current program.

Passivation of the SASS train with 15 percent by volume HNO_3 solution was performed prior to equipment preparation and sampling to produce biologically inert surfaces. Detailed descriptions of equipment preparation, sampling procedures, and sample recovery are discussed in Reference A-2 and will not be repeated here. These procedures were followed in the course of the current test program.

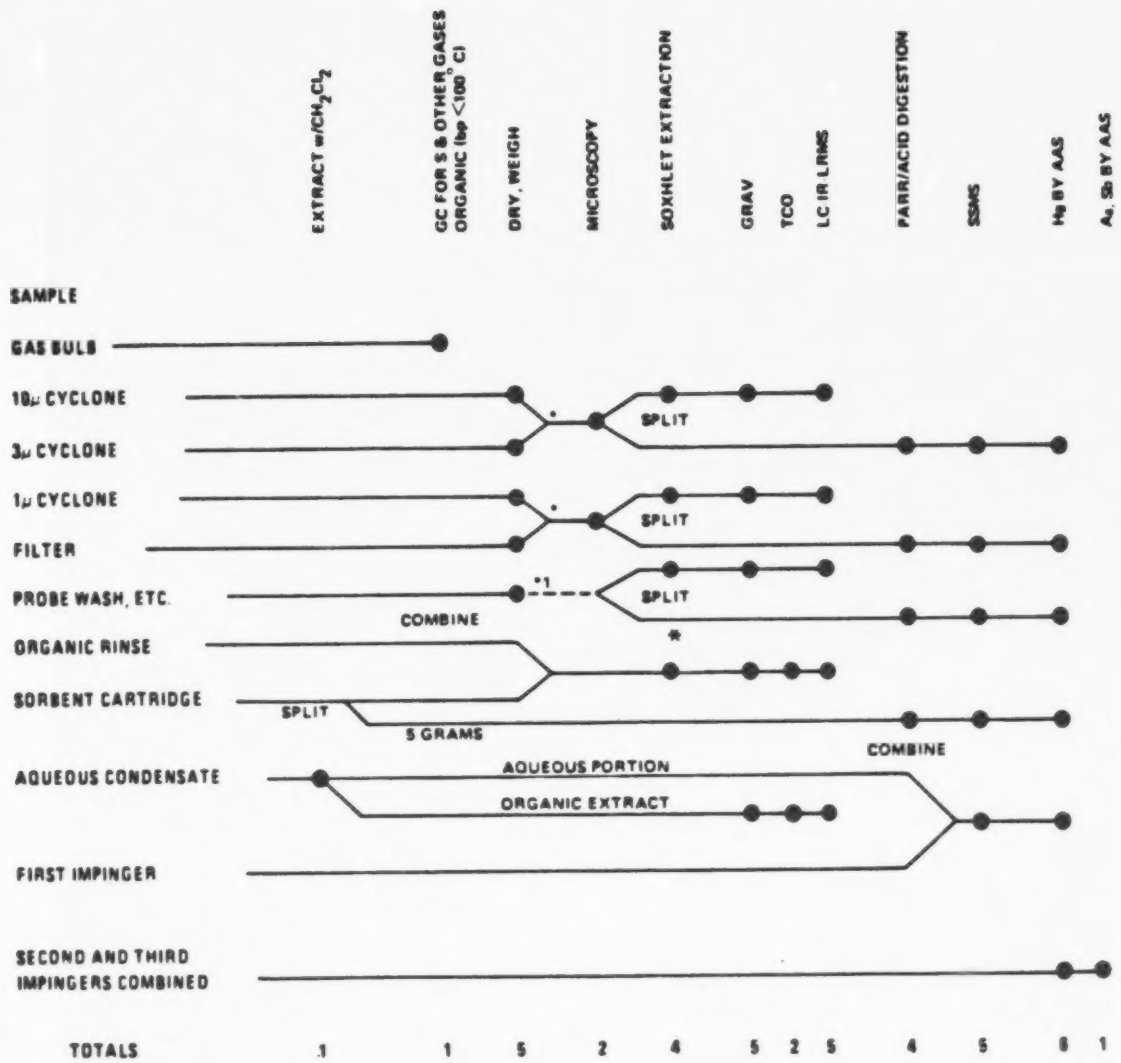
A.5 C_1 TO C_6 HYDROCARBON SAMPLING AND ANALYSIS

Acurex used a grab sampling procedure in order to obtain a sample of exhaust gas for C_1 to C_6 hydrocarbon analysis. Samples of the exhaust gas were extracted using a heated glass probe (Figure A-9). The probe was attached to a heated 250-ml gas sampling bulb. The probe was maintained at 420K (300°F) and the gas sampling bulb at 403K (265°F). A diaphragm pump was



*Analysis when ≥ 10 percent of the total particulate catch.

Figure A-6. Exhaust gas analysis protocol.



* If required, sample should be set aside for biological analysis at this point.

[1] This step is required to define the total mass of particulate catch. If the sample exceeds 10% of the total cyclone and filter sample weight proceed to analysis. If the sample is less than 10% of the catch, hold in reserve.

Figure A-7. Analysis protocol for SASS samples.

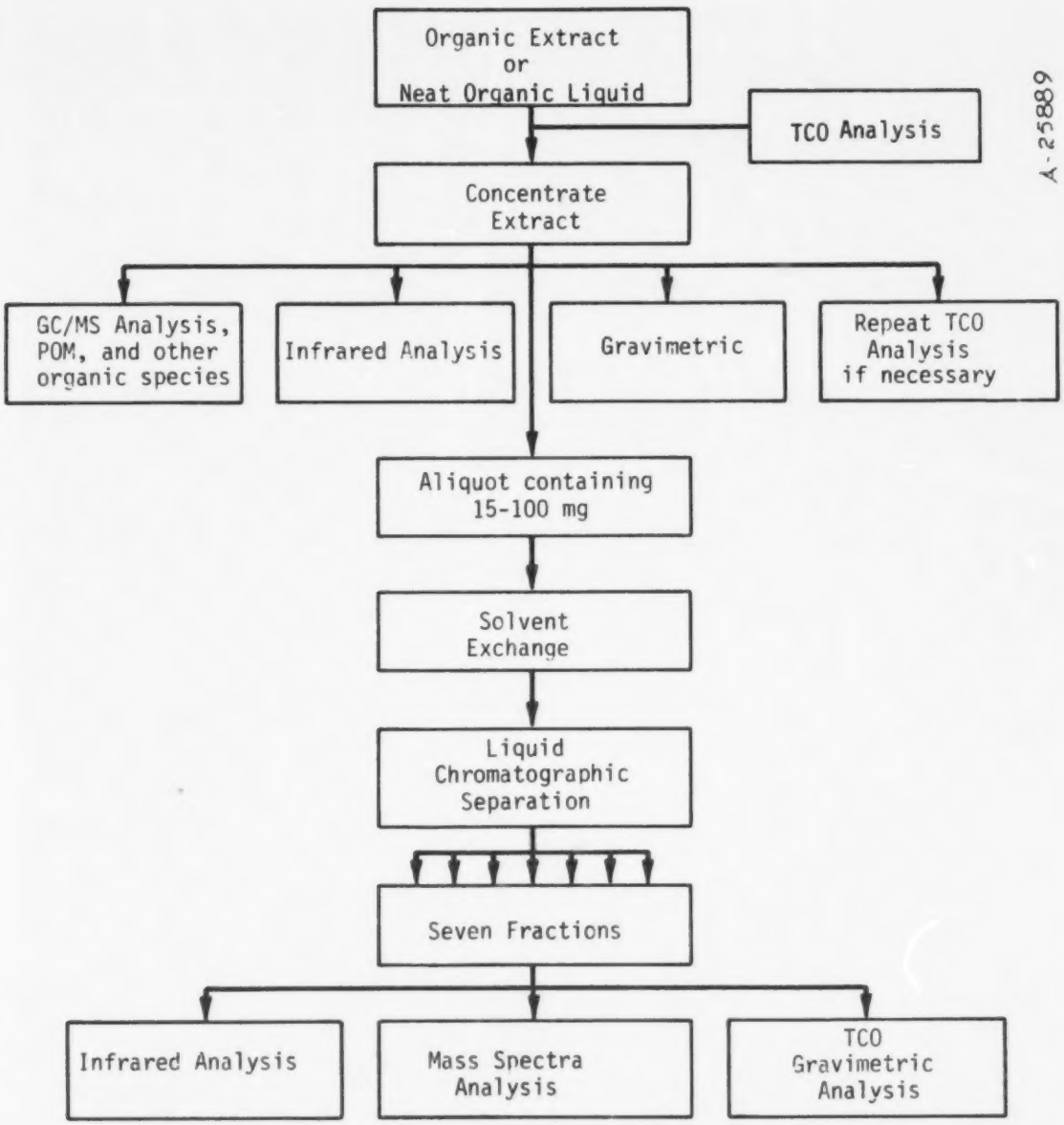
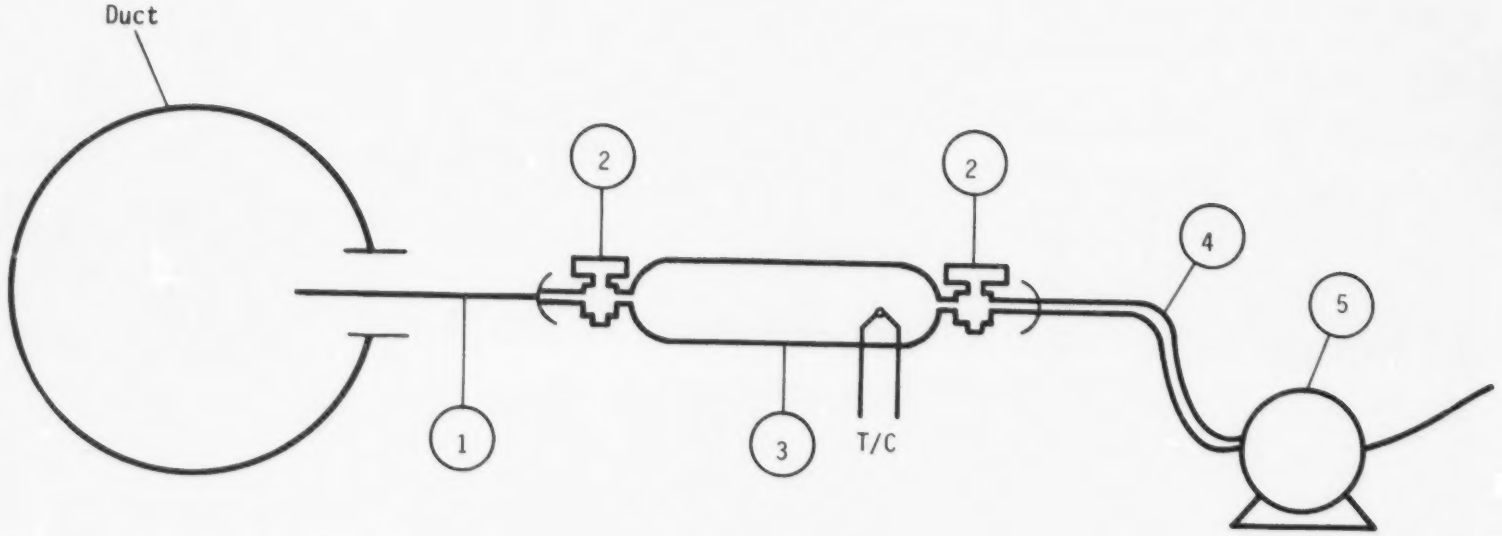


Figure A-8. Organic analysis methodology.



1. Heated glass probe
2. Teflon stopcock
3. 250-ml heated glass gas sampling bulb
4. Tubing connection
5. Sample pump (1 cfm)

Figure A-9. C_1 - C_6 hydrocarbon sampling system.

used to pull samples through the probe and sampling bulb. This purge was continued until all visual signs of condensation had disappeared. At that time, the back stopcock of the sampling bulb was closed and the pump was disconnected. Once the sampling bulb pressure had come to equilibrium with the stack pressure, the sample was sealed and transported to the onsite laboratory for analysis.

The gas sampling bulbs were equipped with a septum port. A gas-tight syringe was used to extract a measured amount of sample. Samples were analyzed onsite with a GC with a FID. Both methane and nonmethane hydrocarbons were measured with each injection using a Carle Model 8500 gas Chromatograph with a FID. Table A-2 details the instrument specifications.

The GC was calibrated before and after each test in order to determine instrument drift. Blank samples were also run in order to quantify any sampling equipment interferences.

Sample data were recorded continuously on a strip chart recorder. After the detection of the methane peak, the column was back-flushed to the detector for analysis of the remaining nonmethane hydrocarbons. Each gas sampling bulb was analyzed several times to ensure a representative sample analysis.

TABLE A-2. GAS CHROMATOGRAPH SPECIFICATIONS

Carle Instruments, Inc., Model 8500 gas chromatograph:	
Sensitivity:	5×10^{-12} amperes for 1 mV output
Supression range:	10^{-9} amperes
Noise:	0.5% peak to peak on most sensitive range
Time constant:	100 milliseconds on all ranges except "1" range which is 200 milliseconds
Gas required:	Carrier gas (helium) Combustion air Fuel gas (hydrocarbon)

REFERENCES FOR APPENDIX A

A-1. "DEMA Exhaust Emission Measurement Procedure for Low and Medium Speed Internal Combustion Engines," Diesel Engine Manufacturers Association, Cleveland, Ohio, 1974.

A-2. Lentzen, D.E. et al., "IERL-RTP Procedures Manual; Level 1 Environmental Assessment (Second Edition)," EPA-600/7-78-201, NTIS PB293795, October 1978.

APPENDIX B

TRACE ELEMENT CONCENTRATIONS

The following tables present sample trace element analysis results and trace element discharge stream concentrations. The tables labeled "ppm" represent element analysis results (microgram per gram) for each sample analyzed. Compositions for the engine lube oil, diesel fuel, and all SASS train samples (filter, XAD-2 resin, and first impinger) are noted. Other tables give corresponding sample element concentrations in units of µg/dscm and ng/J heat input. A final set of tables gives corresponding trace element flowrates in µg/s, with the mass balance ratio (out/in) noted.

Symbols appearing in the tables include:

DSCM	Dry standard cubic meter at 1 atm and 15°C
MCG	Microgram
PPM	Part per million by weight
SEC	Second
<	Less than
>	Greater than

Trace elements having concentrations less than the detectable limit or having a blank value greater than the sample value were given an arbitrary concentration of zero.

Detectability limits for the various SASS samples were:

- Filter: <0.001 μg/cm^2
  - -- Baseline: <2.1 μg/g
  - -- Low-NO_x: <3.7 μg/g
- XAD-2: <0.1 μg/g
- Impinger and organic module concentrate: <0.001 μ/ml
- Lube oil: <0.03 μg/g

The difference between the μg/g detection limits for the SASS filter between the baseline and low-NO_x tests was due to the different amount of particulate caught on the filter. Filter analyses results are in terms of μg/cm^2 of filter area, which is multiplied by the filter catch (g ash/cm^3 filter), to give the filter particulate analysis result.

DIESEL NOX CONTROL
BASELINE

PPM

ELEMENT	DIESEL FUEL	LUBE OIL	FILTER	XAD	IMPINGER 1+ OMC
ALUMINUM	>.210E+02	.700E+00	U.000E+00	>.870E+02	U.000E+00
ANTIMONY	.000E+00	.200E-01	.000E+00	.000E+00	.200E-02
ARSENIC	.000E+00	.100E+01	.345E+00	.000E+00	.100E-02
BARIUM	.800E+00	.500E+02	.000E+00	.000E+00	.100E-01
BERYLLIUM	.000E+00	<.100E-01	<.345E+00	.000E+00	.000E+00
BISMUTH	.000E+00	.000E+00	<.345E+00	.000E+00	.000E+00
BORON	.200E-01	<.100E-01	.379E+03	.000E+00	.400E-02
BROMINE	.400E+00	.700E+00	.000E+00	.500E+00	.700E-02
CADMIUM	.000E+00	.700E-01	<.345E+01	.000E+00	.200E-01
CALCIUM	.510E+02	>.100E+03	U.000E+00	.000E+00	.800E+01
CERIUM	.000E+00	.000E+00	.000E+00	.000E+00	.100E-02
CESIUM	.000E+00	.100E-01	<.345E+00	.000E+00	<.100E-02
CHLORINE	.700E+00	.530E+02	.000E+00	.000E+00	.100E+00
CHROMIUM	.500E-01	.700E+01	.345E+01	.000E+00	.290E-01
COBALT	.800E-01	.700E+00	.000E+00	.000E+00	.300E-02
COPPER	.600E+00	.500E+01	.276E+02	.800E+01	.199E+00
FLUORINE	.200E+00	.200E+00	.136E+03	.000E+00	.900E-02
GALLIUM	.000E+00	.500E-01	.000E+00	.000E+00	.500E-02
GERMANIUM	.000E+00	.000E+00	<.345E+00	.000E+00	<.100E-02
GOLD	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
IODINE	<.300E-01	.000E+00	.689E+00	.000E+00	.000E+00
IRON	.100E+02	.850E+02	.103E+03	.000E+00	.300E+01
LANTHANUM	.000E+00	.300E-01	.000E+00	.000E+00	.300E-02
LEAD	.200E+00	.100E+01	.320E+02	.000E+00	.000E+00
LITHIUM	.600E-01	.700E-01	.276E+01	.000E+00	.000E+00
MAGNESIUM	.200E+01	.300E+01	.689E+03	.000E+00	.100E+00
MANGANESE	.200E+00	.500E+00	.138E+01	.000E+00	.800E-01
MERCURY	.000E+00	.000E+00	<.207E+01	<.100E+00	<.100E+01
MOLYBDENUM	.200E+01	.400E+00	.138E+01	.000E+00	.100E-01
NEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00	.300E-02
NICKEL	.700E+00	.200E+01	.345E+01	U.000E+00	.170E+00
NIOBIUM	.000E+00	.000E+00	.000E+00	.000E+00	<.100E-02
PHOSPHORUS	.700E+01	.600E+01	.448E+02	.000E+00	>.910E+01
POTASSIUM	.440E+02	>.100E+03	.000E+00	>.760E+02	>.950E+01
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.000E+00	.400E-01	.000E+00	.000E+00	.900E-02
SAMARIUM	.000E+00	.000E+00	.345E+00	.000E+00	.000E+00
SCANDIUM	.200E-01	<.200E-01	.000E+00	.000E+00	.100E+00
SELENIUM	.000E+00	.300E+00	.000E+00	.000E+00	.300E+00
SILICON	.150E+02	.960E+02	U.000E+00	U.000E+00	.400E+01
SILVER	.000E+00	.100E-01	.000E+00	.300E+00	.100E+00
SODIUM	.100E+01	>.100E+03	U.000E+00	.000E+00	>.950E+01
STRONTIUM	.100E+00	.230E+02	.000E+00	.200E+00	.200E-02
SULFUR	.190E+04	.960E+04	>.317E+04	.390E+02	>.980E+01
TANTALUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00

DIESEL NOX CONTROL
BASELINE

PPM

ELEMENT	DIESEL FUEL	LUBE OIL	FILTER	XAD	IMPINGER 1+ OMC
TELLURIUM	.000E+00	.000E+00	.172E+01	.000E+00	.000E+00
THORIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
TIN	.000E+00	.200E+00	.207E+01	.000E+00	.700E-01
TITANIUM	.200E+01	.700E+01	.000E+00	.000E+00	.310E+00
TUNGSTEN	<.100E+00	.000E+00	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.400E-01	.400E-01	.000E+00	.000E+00	.100E-02
YTTRIUM	.000E+00	.000E+00	.000E+00	.000E+00	<.100E-02
ZINC	.900E+00	.180E+02	.310E+02	.000E+00	.970E+00
ZIRCONIUM	.900E-01	.000E+00	.103E+02	.000E+00	.900E-02

DIESEL NOX CONTROL
BASELINE
MCG/DSCM

CONCENTRATION ELEMENT	FILTER	XAD	IMPINGER 1+ OMC	EXHAUST
ALUMINUM	U .000E+00	> .689E+03	U .000E+00	> .689E+03
ANTIMONY	.000E+00	.000E+00	.174E+00	.174E+00
ARSENIC	.965E-02	.000E+00	.868E-01	.965E-01
BARIUM	.000E+00	.000E+00	.868E+00	.868E+00
BERYLLIUM	< .965E-02	.000E+00	.000E+00	< .965E-02
BISMUTH	< .965E-02	.000E+00	.000E+00	< .965E-02
BORON	.106E+02	.000E+00	.347E+00	.110E+02
BROMINE	.000E+00	.396E+01	.608E+00	.457E+01
CADMIUM	< .965E-01	.000E+00	.174E+01	.174E+01<X<.183E+01
CALCIUM	U .000E+00	.000E+00	.695E+03	.695E+03
CERIUM	.000E+00	.000E+00	.868E-01	.868E-01
CESIUM	< .965E-02	.000E+00	< .868E-01	< .965E-01
CHLORINE	.000E+00	.000E+00	.868E+01	.868E+01
CHROMIUM	.965E-01	.000E+00	.252E+01	.261E+01
COBALT	.000E+00	.000E+00	.261E+00	.261E+00
COPPER	.772E+00	.634E+02	.173E+02	.814E+02
FLUORINE	.381E+01	.000E+00	.782E+00	.459E+01
GALLIUM	.000E+00	.000E+00	.434E+00	.434E+00
GERMANIUM	< .965E-02	.000E+00	< .868E-01	< .965E-01
GOLD	.000E+00	.000E+00	.000E+00	.000E+00
IODINE	.193E-01	.000E+00	.000E+00	.193E-01
IRON	.290E+01	.000E+00	.261E+03	.263E+03
LANTHANUM	.000E+00	.000E+00	.261E+00	.261E+00
LEAD	.898E+00	.000E+00	.000E+00	.898E+00
LITHIUM	.772E-01	.000E+00	.000E+00	.772E-01
MAGNESIUM	.193E+02	.000E+00	.868E+01	.280E+02
MANGANESE	.386E-01	.000E+00	.695E+01	.699E+01
MERCURY	< .579E-01	< .792E+00	< .868E+02	< .877E+02
MOLYBDENUM	.386E-01	.000E+00	.868E+00	.907E+00
NEODYMIUM	.000E+00	.000E+00	.261E+00	.261E+00
NICKEL	.965E-01	U .000E+00	.148E+02	.149E+02
NIOBIUM	.000E+00	.000E+00	< .868E-01	< .868E-01
PHOSPHORUS	.125E+01	.000E+00	> .790E+03	> .791E+03
POTASSIUM	.000E+00	> .602E+03	> .825E+03	> .143E+04
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	.782E+00	.782E+00
SAMARIUM	.965E-02	.000E+00	.000E+00	.965E-02
SCANDIUM	.000E+00	.000E+00	.868E+01	.868E+01
SELENIUM	.000E+00	.000E+00	.261E+02	.261E+02
SILICON	U .000E+00	U .000E+00	.347E+03	.347E+03
SILVER	.000E+00	.238E+01	.868E+01	.111E+02
SODIUM	U .000E+00	.000E+00	> .825E+03	> .825E+03
STRONTIUM	.000E+00	.158E+01	.174E+00	.176E+01
SULFUR	> .888E+02	.309E+03	> .851E+03	> .125E+04
TANTALUM	.000E+00	.000E+00	.000E+00	.000E+00

DIESEL NOX CONTROL
BASELINE

CONCENTRATION MCG/DSCM ELEMENT	FILTER	XAD	IMPINGER 1+ OMC	EXHAUST
TELLURIUM	.483E-01	.000E+00	.000E+00	.483E-01
THORIUM	.000E+00	.000E+00	.000E+00	.000E+00
TIN	.579E-01	.000E+00	.608E+01	.614E+01
TITANIUM	.000E+00	.000E+00	.269E+02	.269E+02
TUNGSTEN	.000E+00	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.000E+00	.000E+00	.868E-01	.868E-01
YTTRIUM	.000E+00	.000E+00	< .868E-01	< .868E-01
ZINC	.869E+00	.000E+00	.842E+02	.851E+02
ZIRCONIUM	.290E+00	.000E+00	.782E+00	.107E+01

DIESEL NOX CONTROL
BASELINE

MASS/HEAT INPUT NG/J

ELEMENT	FILTER	XAD	IMPINGER 1+ OMC	EXHAUST
ALUMINUM	U .000E+00	> .530E+00	U .000E+00	> .530E+00
ANTIMONY	.000E+00	.000E+00	.133E-03	.133E-03
ARSENIC	.742E-05	.000E+00	.667E-04	.741E-04
BARIUM	.000E+00	.000E+00	.667E-03	.667E-03
BERYLLIUM	< .742E-05	.000E+00	.000E+00	< .742E-05
BISMUTH	< .742E-05	.000E+00	.000E+00	< .742E-05
BORON	.816E-02	.000E+00	.267E-03	.842E-02
BROMINE	.000E+00	.304E-02	.467E-03	.351E-02
CADMIUM	< .742E-04	.000E+00	.133E-02	.133E-02<X<.141E-02
CALCIUM	U .000E+00	.000E+00	.534E+00	.534E+00
CERIUM	.000E+00	.000E+00	.667E-04	.667E-04
CESIUM	< .742E-05	.000E+00	< .667E-04	< .741E-04
CHLORINE	.000E+00	.000E+00	.667E-02	.667E-02
CHROMIUM	.742E-04	.000E+00	.193E-02	.201E-02
COBALT	.000E+00	.000E+00	.200E-03	.200E-03
COPPER	.593E-03	.487E-01	.133E-01	.626E-01
FLUORINE	.293E-02	.000E+00	.601E-03	.353E-02
GALLIUM	.000E+00	.000E+00	.334E-03	.334E-03
GERMANIUM	< .742E-05	.000E+00	< .667E-04	< .741E-04
GOLD	.000E+00	.000E+00	.000E+00	.000E+00
IODINE	.148E-04	.000E+00	.000E+00	.148E-04
IRON	.222E-02	.000E+00	.200E+00	.202E+00
LANTHANUM	.000E+00	.000E+00	.200E-03	.200E-03
LEAD	.690E-03	.000E+00	.000E+00	.690E-03
LITHIUM	.593E-04	.000E+00	.000E+00	.593E-04
MAGNESIUM	.148E-01	.000E+00	.667E-02	.215E-01
MANGANESE	.297E-04	.000E+00	.534E-02	.537E-02
MERCURY	< .445E-04	< .609E-03	< .667E-01	< .674E-01
MOLYBDENUM	.297E-04	.000E+00	.667E-03	.697E-03
NEODYMIUM	.000E+00	.000E+00	.200E-03	.200E-03
NICKEL	.742E-04	U .000E+00	.113E-01	.114E-01
NIOBIUM	.000E+00	.000E+00	< .667E-04	< .667E-04
PHOSPHORUS	.964E-03	.000E+00	> .607E+00	> .608E+00
POTASSIUM	.000E+00	> .463E+00	> .634E+00	> .110E+01
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	.601E-03	.601E-03
SAMARIUM	.742E-05	.000E+00	.000E+00	.742E-05
SCANDIUM	.000E+00	.000E+00	.667E-02	.667E-02
SELENIUM	.000E+00	.000E+00	.200E-01	.200E-01
SILICON	U .000E+00	U .000E+00	.267E+00	.267E+00
SILVER	.000E+00	.183E-02	.667E-02	.850E-02
SODIUM	U .000E+00	.000E+00	> .634E+00	> .634E+00
STRONTIUM	.000E+00	.122E-02	.133E-03	.135E-02
SULFUR	> .682E-01	.237E+00	> .654E+00	> .960E+00
TANTALUM	.000E+00	.000E+00	.000E+00	.000E+00

DIESEL NOX CONTROL
BASELINE

MASS/HEAT INPUT NG/J

ELEMENT	FILTER	XAD	IMPINGER 1+ OMC	EXHAUST
TELLURIUM	.371E-04	.000E+00	.000E+00	.371E-04
THORIUM	.000E+00	.000E+00	.000E+00	.000E+00
TIN	.445E-04	.000E+00	.467E-02	.472E-02
TITANIUM	.000E+00	.000E+00	.207E-01	.207E-01
TUNGSTEN	.000E+00	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.000E+00	.000E+00	.667E-04	.667E-04
YTTRIUM	.000E+00	.000E+00	< .667E-04	< .667E-04
ZINC	.667E-03	.000E+00	.647E-01	.654E-01
ZIRCONIUM	.222E-03	.000E+00	.601E-03	.823E-03

DIESEL NOX CONTROL
BASELINE

MASS/HEAT INPUT
NG/J

ELEMENT	DIESEL FUEL	LUBE OIL	EXHAUST
ALUMINUM	> .478E+00	.181E-01	> .530E+00
ANTIMONY	.000E+00	.460E-03	.133E-03
ARSENIC	.000E+00	.230E-01	.741E-04
BARIUM	.182E-01	.115E+01	.667E-03
BERYLLIUM	.000E+00	< .230E-03	< .742E-05
BISMUTH	.000E+00	.000E+00	< .742E-05
BORON	.456E-03	< .230E-03	.842E-02
BROMINE	.911E-02	.161E-01	.351E-02
CADMIUM	.000E+00	.161E-02	.133E-02<X<.141E-02
CALCIUM	.116E+01	> .230E+01	.534E+00
CERIUM	.000E+00	.000E+00	.667E-04
CESIUM	.000E+00	.230E-03	< .741E-04
CHLORINE	.159E-01	.122E+01	.667E-02
CHROMIUM	.114E-02	.161E+00	.201E-02
COBALT	.182E-02	.161E-01	.200E-03
COPPER	.137E-01	.115E+00	.820E-01
FLUORINE	.456E-02	.460E-02	.353E-02
GALLIUM	.000E+00	.115E-02	.334E-03
GERMANIUM	.000E+00	.000E+00	< .741E-04
GOLD	.000E+00	.000E+00	.000E+00
IODINE	< .683E-03	.000E+00	.148E-04
IRON	.228E+00	.196E+01	.202E+00
LANTHANUM	.000E+00	.690E-03	.200E-03
LEAD	.456E-02	.230E-01	.690E-03
LITHIUM	.137E-02	.161E-02	.593E-04
MAGNESIUM	.456E-01	.690E-01	.215E-01
MANGANESE	.456E-02	.115E-01	.537E-02
MERCURY	.000E+00	.000E+00	< .674E-01
MOLYBDENUM	.456E-01	.920E-02	.697E-03
NEODYMIUM	.000E+00	.000E+00	.200E-03
NICKEL	.159E-01	.460E-01	.114E-01
NIOBIUM	.000E+00	.000E+00	< .667E-04
PHOSPHORUS	.159E+00	.138E+00	> .608E+00
POTASSIUM	.100E+01	> .230E+01	> .110E+01
PRASEODYMIUM	.000E+00	.000E+00	.000E+00
RUBIDIUM	.000E+00	.920E-03	.601E-03
SAMARIUM	.000E+00	.000E+00	.742E-05
SCANDIUM	.456E-03	< .460E-03	.667E-02
SELENIUM	.000E+00	.690E-02	.200E-01
SILICON	.342E+00	.221E+01	.267E+00
SILVER	.000E+00	.230E-03	.850E-02
SODIUM	.22RE-01	> .230E+01	> .634E+00
STRONTIUM	.22RE-02	.529E+00	.135E-02
SULFUR	.433E+02	.221E+03	> .960E+00
TANTALUM	.000E+00	.000E+00	.000E+00

DIESEL NOX CONTROL

MASS/HEAT INPUT — BASELINE

NG/J

ELEMENT	DIESEL FUEL	LUBE OIL	EXHAUST
TELLURIUM	.000E+00	.000E+00	.371E-04
THORIUM	.000E+00	.000E+00	.000E+00
TIN	.000E+00	.460E-02	.472E-02
TITANIUM	.456E-01	.161E+00	.207E-01
TUNGSTEN	< .228E-02	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00
VANADIUM	.911E-03	.920E-03	.667E-04
YTTRIUM	.000E+00	.000E+00	< .667E-04
ZINC	.205E-01	.414E+00	.654E-01
ZIRCONIUM	.205E-02	.000E+00	.823E-03

DIESEL NOX CONTROL
BASELINE
MASS FLOW MCG/SEC

ELEMENT	FILTER	XAD	IMPINGER 1+ OMC	EXHAUST
ALUMINUM	U .000E+00	> .228E+04	U .000E+00	> .228E+04
ANTIMONY	.000E+00	.000E+00	.576E+00	.576E+00
ARSENIC	.320E-01	.000E+00	.288E+00	.320E+00
BARIUM	.000E+00	.000E+00	.288E+01	.288E+01
BERYLLIUM	< .320E-01	.000E+00	.000E+00	< .320E-01
BISMUTH	< .320E-01	.000E+00	.000E+00	< .320E-01
BORON	.352E+02	.000E+00	.115E+01	.363E+02
BROMINE	.000E+00	.131E+02	.201E+01	.151E+02
CADMIUM	< .320E+00	.000E+00	.576E+01	.576E+01<X<.608E+01
CALCIUM	U .000E+00	.000E+00	.230E+04	.230E+04
CERIUM	.000E+00	.000E+00	.288E+00	.288E+00
CESIUM	< .320E-01	.000E+00	< .288E+00	< .320E+00
CHLORINE	.000E+00	.000E+00	.288E+02	.288E+02
CHROMIUM	.320E+00	.000E+00	.835E+01	.866E+01
COBALT	.000E+00	.000E+00	.863E+00	.863E+00
COPPER	.256E+01	.210E+03	.573E+02	.270E+03
FLUORINE	.126E+02	.000E+00	.259E+01	.152E+02
GALLIUM	.000E+00	.000E+00	.144E+01	.144E+01
GERMANIUM	< .320E-01	.000E+00	< .288E+00	< .320E+00
GOLD	.000E+00	.000E+00	.000E+00	.000E+00
IODINE	.640E-01	.000E+00	.000E+00	.640E-01
IRON	.959E+01	.000E+00	.863E+03	.873E+03
LANTHANUM	.000E+00	.000E+00	.863E+00	.863E+00
LEAD	.297E+01	.000E+00	.000E+00	.297E+01
LITHIUM	.256E+00	.000E+00	.000E+00	.256E+00
MAGNESIUM	.640E+02	.000E+00	.288E+02	.927E+02
MANGANESE	.128E+00	.000E+00	.230E+02	.231E+02
MERCURY	< .192E+00	< .263E+01	< .288E+03	< .291E+03
MOLYBDENUM	.128E+00	.000E+00	.288E+01	.301E+01
NEODYMIUM	.000E+00	.000E+00	.863E+00	.863E+00
NICKEL	.320E+00	U .000E+00	.489E+02	.492E+02
NIOBIUM	.000E+00	.000E+00	< .288E+00	< .288E+00
PHOSPHORUS	.416E+01	.000E+00	> .262E+04	> .262E+04
POTASSIUM	.000E+00	> .200E+04	> .273E+04	> .473E+04
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	.259E+01	.259E+01
SAMARIUM	.320E-01	.000E+00	.000E+00	.320E-01
SCANDIUM	.000E+00	.000E+00	.288E+02	.288E+02
SELENIUM	.000E+00	.000E+00	.863E+02	.863E+02
SILICON	U .000E+00	U .000E+00	.115E+04	.115E+04
SILVER	.000E+00	.788E+01	.288E+02	.367E+02
SODIUM	U .000E+00	.000E+00	> .273E+04	> .273E+04
STRONTIUM	.000E+00	.525E+01	.576E+00	.583E+01
SULFUR	> .294E+03	.102E+04	> .282E+04	> .414E+04
TANTALUM	.000E+00	.000E+00	.000E+00	.000E+00

DIESEL NOX CONTROL
BASELINE

MASS FLOW MCG/SEC

ELEMENT	FILTER	XAD	IMPINGER 1+ CMC	EXHAUST
TELLURIUM	.160E+00	.000E+00	.000E+00	.160E+00
THORIUM	.000E+00	.000E+00	.000E+00	.000E+00
TIN	.192E+00	.000E+00	.201E+02	.203E+02
TITANIUM	.000E+00	.000E+00	.892E+02	.892E+02
TUNGSTEN	.000E+00	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.000E+00	.000E+00	.288E+00	.288E+00
YTTRIUM	.000E+00	.000E+00	< .288E+00	< .288E+00
ZINC	.288E+01	.000E+00	.279E+03	.282E+03
ZIRCONIUM	.959E+00	.000E+00	.259E+01	.355E+01

DIESEL NOX CONTROL
BASELINE

MASS FLOW
MCG/SEC

ELEMENT	DIESEL FUEL	LUBE OIL	EXHAUST
ALUMINUM	> .206E+04	.247E+00	> .228E+04
ANTIMONY	.000E+00	.706E-02	.576E+00
ARSENIC	.000E+00	.353E+00	.320E+00
BARIUM	.783E+02	.176E+02	.288E+01
BERYLLIUM	.000E+00	< .353E-02	< .320E-01
BISMUTH	.000E+00	.000E+00	< .320E-01
BORON	.196E+01	< .353E-02	.363E+02
BROMINE	.392E+02	.247E+00	.151E+02
CADMIUM	.000E+00	.247E-01	.576E+01<X<.608E+01
CALCIUM	.499E+04	> .353E+02	.230E+04
CERIUM	.300E+00	.000E+00	.288E+00
CESIUM	.000E+00	.353E-02	< .320E+00
CHLORINE	.685E+02	.187E+02	.288E+02
CHROMIUM	.489E+01	.247E+01	.866E+01
COBALT	.783E+01	.247E+00	.863E+00
COPPER	.587E+02	.176E+01	.270E+03
FLUORINE	.196E+02	.706E-01	.152E+02
GALLIUM	.000E+00	.176E-01	.144E+01
GERMANIUM	.000E+00	.000E+00	< .320E+00
GOLD	.000E+00	.000E+00	.000E+00
IODINE	< .294E+01	.000E+00	.640E-01
IRON	.979E+03	.300E+02	.873E+03
LANTHANUM	.000E+00	.106E-01	.863E+00
LEAD	.196E+02	.353E+00	.297E+01
LITHIUM	.587E+01	.247E-01	.256E+00
MAGNESIUM	.196E+03	.106E+01	.927E+02
MANGANESE	.196E+02	.176E+00	.231E+02
MERCURY	.000E+00	.000E+00	< .291E+03
MOLYBDENUM	.196E+03	.141E+00	.301E+01
NEODYMIUM	.000E+00	.000E+00	.863E+00
NICKEL	.685E+02	.706E+00	.492E+02
NIOBIUM	.000E+00	.000E+00	< .288E+00
PHOSPHORUS	.685E+03	.212E+01	> .262E+04
POTASSIUM	.431E+04	> .353E+02	> .473E+04
PRASEODYMIUM	.000E+00	.000E+00	.000E+00
RUBIDIUM	.000E+00	.141E-01	.259E+01
SAMARIUM	.000E+00	.000E+00	.320E-01
SCANDIUM	.196E+01	< .706E-02	.288E+02
SELENIUM	.000E+00	.106E+00	.863E+02
SILICON	.147E+04	.339E+02	.115E+04
SILVER	.000E+00	.353E-02	.367E+02
SODIUM	.979E+02	> .353E+02	> .273E+04
STRONTIUM	.979E+01	.812E+01	.583E+01
SULFUR	.186E+06	.339E+04	> .414E+04
TANTALUM	.000E+00	.000E+00	.000E+00

DIESEL NOX CONTROL
BASELINE

MASS FLOW MCG/SEC

ELEMENT	DIESEL FUEL	LUBE OIL	EXHAUST
TELLURIUM	.000E+00	.000E+00	.160E+00
THORIUM	.000E+00	.000E+00	.000E+00
TIN	.000E+00	.706E-01	.203E+02
TITANIUM	.196E+03	.247E+01	.892E+02
TUNGSTEN	< .979E+01	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00
VANADIUM	.392E+01	.141E-01	.288E+00
YTTRIUM	.000E+00	.000E+00	< .288E+00
ZINC	.881E+02	.635E+01	.282E+03
ZIRCONIUM	.881E+01	.000E+00	.355E+01

DIESEL NOX CONTROL
BASELINE

ENGINE MASS-BALANCE

ELEMENT	INPUT = DIESEL FUEL + LUBE OIL TOTAL IN	TOTAL OUT	OUTPUT = EXHAUST MASS BALANCE (OUT/IN)
ALUMINUM	.206E+04 <X	.228E+04 <X	•
ANTIMONY	.706E-02	.576E+00	.815E+02
ARSENIC	.353E+00	.320E+00	.906E+00
BARIUM	.960E+02	.288E+01	.300E-01
BERYLLIUM	X<.353E-02	X<.320E-01	•
BISMUTH		X<.320E-01	•
BORON	.196E+01	.363E+02	.185E+02
BROMINE	.394E+02	.151E+02	.384E+00
CADMIUM	.247E-01	.576E+01<X<.608E+01	.233E+03<X<.246E+03
CALCIUM	.503E+04 <X	.230E+04	X<.458E+00
CERIUM		.288E+00	•
CESIUM	.353E-02	X<.320E+00	.000E+00<X<.906E+02
CHLORINE	.872E+02	.288E+02	.330E+00
CHROMIUM	.737E+01	.866E+01	.118E+01
COBALT	.808E+01	.863E+00	.107E+00
COPPER	.605E+02	.270E+03	.446E+01
FLUORINE	.197E+02	.152E+02	.775E+00
GALLIUM	.176E-01	.144E+01	.815E+02
GERMANIUM		X<.320E+00	•
GOLD			•
IODINE	X<.294E+01	.640E-01	.218E-01 <X
IRON	.101E+04	.873E+03	.865E+00
LANTHANUM	.106E-01	.863E+00	.815E+02
LEAD	.199E+02	.297E+01	.149E+00
LITHIUM	.590E+01	.256E+00	.434E-01
MAGNESIUM	.197E+03	.927E+02	.471E+00
MANGANESE	.198E+02	.231E+02	.117E+01
MERCURY		X<.291E+03	•
MOLYBDENUM	.196E+03	.301E+01	.153E-01
NEODYMIUM		.863E+00	•
NICKEL	.692E+02	.492E+02	.711E+00
NIOBIUM		X<.288E+00	•
PHOSPHORUS	.687E+03	.262E+04 <X	.382E+01 <X
POTASSIUM	.434E+04 <X	.473E+04 <X	•
PRASEODYMIUM			•
RUBIDIUM	.141E-01	.259E+01	.183E+03
SAMARIUM		.320E-01	•
SCANDIUM	.197E+01	.288E+02	.146E+02
SELENIUM	.106E+00	.863E+02	.815E+03
SILICON	.150E+04	.115E+04	.766E+00
SILVER	.353E-02	.367E+02	.104E+05
SODIUM	.133E+03 <X	.273E+04 <X	•
STRONTIUM	.179E+02	.583E+01	.325E+00
SULFUR	.189E+06	.414E+04 <X	.218E-01 <X
TANTALUM			•

DIESEL NOX CONTROL
BASELINE

ENGINE MASS-BALANCE

INPUT = DIESEL FUEL + LUBE OIL

OUTPUT = EXHAUST

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OUT/IN)
TELLURIUM		.160E+00	•
THORIUM			•
TIN	.706E-01	.203E+02	.288E+03
TITANIUM	.198E+03	.892E+02	.450E+00
TUNGSTEN	X<.979E+01		.000E+00
URANIUM			•
VANADIUM	.393E+01	.288E+00	.732E-01
YTTRIUM		X<.288E+00	•
ZINC	.945E+02	.282E+03	.299E+01
ZIRCONIUM	.881E+01	.355E+01	.403E+00

DIESEL NOX CONTROL
LOW NOX

PPM ELEMENT	PPM DIESEL FUEL	LUBE OIL	FILTER	XAD	IMPINGER 1+ OMC
ALUMINUM	.500E+01	.700E+00	U.000E+00	.200E+01	U.000E+00
ANTIMONY	.700E-01	.200E-01	<.200E+00	.000E+00	.700E-02
ARSENIC	.000E+00	.100E+01	.200E+00	.000E+00	<.100E-02
BARIUM	.300E+00	.500E+02	.000E+00	.300E+01	.100E-01
BERYLLIUM	.000E+00	<.100E-01	.000E+00	.000E+00	.000E+00
BISMUTH	.000E+00	.000E+00	<.200E+00	.000E+00	.000E+00
BORON	<.100E-01	<.100E-01	.000E+00	.100E+00	.000E+00
BROMINE	.800E-01	.700E+00	.000E+00	.000E+00	.170E-01
CADMIUM	.000E+00	.700E-01	<.200E+00	.000E+00	.600E-02
CALCIUM	.190E+02	>.100E+03	U.000E+00	.000E+00	.000E+00
CERIUM	.200E-01	.000E+00	.000E+00	.000E+00	.000E+00
CESIUM	.000E+00	.100E-01	.000E+00	.000E+00	<.100E-02
CHLORINE	.300E+00	.530E+02	.000E+00	.000E+00	.000E+00
CHROMIUM	.100E+00	.700E+01	.000E+00	.100E+01	.990E-01
COBALT	.400E-01	.700E+00	.000E+00	.100E+01	.130E-01
COPPER	.200E+00	.500E+01	.800E+01	.220E+02	.400E+01
FLUORINE	.300E+01	.200E+00	.000E+00	.000E+00	.900E+00
GALLIUM	.000E+00	.500E-01	.000E+00	.100E+00	.100E-01
GERMANIUM	.000E+00	.000E+00	<.200E+00	.000E+00	<.100E-02
GOLD	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
IODINE	.000E+00	.000E+00	.200E+00	.000E+00	.000E+00
IRON	.400E-01	.850E+02	.000E+00	.190E+03	.000E+00
LANTHANUM	.200E-01	.300E-01	.000E+00	.000E+00	.000E+00
LEAD	.300E+00	.100E+01	.166E+02	.140E+01	.000E+00
LITHIUM	.400E-01	.700E-01	.000E+00	.200E+00	.300E-02
MAGNESIUM	.100E+01	.300E+01	.000E+00	.000E+00	.000E+00
MANGANESE	.500E-01	.500E+00	.600E+00	.000E+00	.200E-01
MERCURY	.000E+00	.000E+00	<.200E+01	.000E+00	.000E+00
MOLYBDENUM	.200E+00	.400E+00	.000E+00	.500E+00	.000E+00
NEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
NICKEL	.400E+00	.200E+01	.000E+00	U.000E+00	.600E-01
NIOBIUM	.000E+00	.000E+00	.000E+00	.000E+00	.200E-02
PHOSPHORUS	.500E+00	.600E+01	.400E+01	.800E+01	.100E+00
POTASSIUM	.580E+02	>.100E+03	.600E+02	.120E+02	>.950E+01
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.100E-01	.400E-01	.000E+00	.000E+00	0.000E+00
SAMARIUM	.000E+00	.000E+00	.200E+00	.000E+00	.000E+00
SCANDIUM	<.100E-01	<.200E-01	.000E+00	.000E+00	<.200E-02
SELENIUM	.000E+00	.300E+00	.000E+00	.000E+00	.400E+00
SILICON	.500E+01	.960E+02	U.000E+00	U.000E+00	.900E+01
SILVER	.200E+00	.100E-01	.000E+00	<.100E+00	.200E-01
SODIUM	.400E+01	>.100E+03	U.000E+00	.000E+00	>.950E+01
STRONTIUM	.200E+00	.230E+02	.800E+01	.200E+00	.900E-02
SULFUR	.197E+04	.960E+04	.240E+03	.130E+02	>.980E+01
TANTALUM	.000E+00	.000E+00	.000E+00	<.400E+00	.000E+00

DIESEL NOX CONTROL
LOW NOX

PPM

ELEMENT	PPM DIESEL FUEL	LUBE OIL	FILTER	XAD	IMPINGER 1+ OMC
TELLURIUM	.000E+00	.000E+00	.000E+00	.000E+00	.200E-02
THORIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
TIN	.000E+00	.200E+00	.400E+00	.000E+00	.800E-01
TITANIUM	.200E+01	.700E+01	.000E+00	.000E+00	.100E-01
TUNGSTEN	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.200E-01	.400E-01	.000E+00	.000E+00	.100E-02
YTTRIUM	.000E+00	.000E+00	.000E+00	.000E+00	.100E-02
ZINC	.600E+00	.180E+02	.120E+02	.110E+02	.297E+01
ZIRCONIUM	.000E+00	.000E+00	.200E+01	.000E+00	.600E-02

DIESEL NOX CONTROL
LOW NOX

CONCENTRATION
MCG/DSCM

ELEMENT	FILTER	XAD	IMPINGER 1+ OMC	EXHAUST
ALUMINUM	U .000E+00	.117E+02	U .000E+00	.117E+02
ANTIMONY	< .711E-02	.000E+00	.478E+00	.478E+00<X<.485E+00
ARSENIC	.711E-02	.000E+00	< .683E-01	.711E-02<X<.754E-01
BARIUM	.000E+00	.175E+02	.683E+00	.182E+02
BERYLLIUM	.000E+00	.000E+00	.000E+00	.000E+00
BISMUTH	< .711E-02	.000E+00	.000E+00	< .711E-02
BORON	.000E+00	.583E+00	.000E+00	.583E+00
BROMINE	.000E+00	.000E+00	.116E+01	.116E+01
CADMIUM	< .711E-02	.000E+00	.410E+00	.410E+00<X<.417E+00
CALCIUM	U .000E+00	.000E+00	.000E+00	.000E+00
CERIUM	.000E+00	.000E+00	.000E+00	.000E+00
CESIUM	.000E+00	.000E+00	< .683E-01	< .683E-01
CHLORINE	.000E+00	.000E+00	.000E+00	.000E+00
CHROMIUM	.000E+00	.583E+01	.676E+01	.126E+02
COBALT	.000E+00	.583E+01	.887E+00	.672E+01
COPPER	.213E+00	.128E+03	.273E+03	.402E+03
FLUORINE	.000E+00	.000E+00	.614E+02	.614E+02
GALLIUM	.000E+00	.583E+00	.683E+00	.127E+01
GERMANIUM	< .711E-02	.000E+00	< .683E-01	< .754E-01
GOLD	.000E+00	.000E+00	.000E+00	.000E+00
IODINE	.711E-02	.000E+00	.000E+00	.711E-02
IRON	.000E+00	.111E+04	.000E+00	.111E+04
LANTHANUM	.000E+00	.000E+00	.000E+00	.000E+00
LEAD	.590E+00	.817E+01	.000E+00	.876E+01
LITHIUM	.000E+00	.117E+01	.205E+00	.137E+01
MAGNESIUM	.000E+00	.000E+00	.000E+00	.000E+00
MANGANESE	.213E-01	.000E+00	.137E+01	.139E+01
MERCURY	< .711E-01	.000E+00	.000E+00	< .711E-01
MOLYBDENUM	.284E-01	.292E+01	.000E+00	.295E+01
NEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00
NICKEL	.000E+00	U .000E+00	.410E+01	.410E+01
NIOBIUM	.000E+00	.000E+00	.137E+00	.137E+00
PHOSPHORUS	.142E+00	.467E+02	.683E+01	.536E+02
POTASSIUM	.213E+01	.700E+02	> .648E+03	> .721E+03
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	0 .000E+00	.000E+00
SAMARIUM	.711E-02	.000E+00	.000E+00	.711E-02
SCANDIUM	.000E+00	.000E+00	< .137E+00	< .137E+00
SELENIUM	.000E+00	.000E+00	.273E+02	.273E+02
SILICON	U .000E+00	U .000E+00	.614E+03	.614E+03
SILVER	.000E+00	< .583E+00	.137E+01	.137E+01<X<.195E+01
SODIUM	U .000E+00	.000E+00	> .648E+03	> .648E+03
STRONTIUM	.284E+00	.117E+01	.614E+00	.207E+01
SULFUR	.853E+01	.758E+02	> .669E+03	> .753E+03
TANTALUM	.000E+00	< .233E+01	.000E+00	< .233E+01

DIESEL NOX CONTROL
LOW NOX

CONCENTRATION MCG/DSCM ELEMENT	FILTER	XAD	IMPINGER 1+ CMC	EXHAUST
TELLURIUM	.000E+00	.000E+00	.137E+00	.137E+00
THORIUM	.000E+00	.000E+00	.000E+00	.000E+00
TIN	.142E-01	.000E+00	.546E+01	.547E+01
TITANIUM	.000E+00	.000E+00	.683E+00	.683E+00
TUNGSTEN	.000E+00	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.000E+00	.000E+00	.683E-01	.683E-01
YTTRIUM	.000E+00	.000E+00	.683E-01	.683E-01
ZINC	.426E+00	.642E+02	.203E+03	.267E+03
ZIRCONIUM	.711E-01	.000E+00	.410E+00	.481E+00

DIESEL NOX CONTROL
LOW NOX

MASS/HEAT INPUT NG/J ELEMENT	FILTER	XAD	IMPINGER 1+ CMC	EXHAUST
ALUMINUM	U .000E+00	.979E-02	U .000E+00	.979E-02
ANTIMONY	< .596E-05	.000E+00	.401E-03	.401E-03<X<.407E-03
ARSENIC	.596E-05	.000E+00	< .573E-04	.596E-05<X<.632E-04
BARIUM	.000E+00	.147E-01	.573E-03	.153E-01
BERYLLIUM	.000E+00	.000E+00	.000E+00	.000E+00
BISMUTH	< .596E-05	.000E+00	.000E+00	< .596E-05
BORON	.000E+00	.490E-03	.000E+00	.490E-03
BROMINE	.000E+00	.000E+00	.974E-03	.974E-03
CADMIUM	< .596E-05	.000E+00	.344E-03	.344E-03<X<.350E-03
CALCIUM	U .000E+00	.000E+00	.000E+00	.000E+00
CERIUM	.000E+00	.000E+00	.000E+00	.000E+00
CESIUM	.000E+00	.000E+00	< .573E-04	< .573E-04
CHLORINE	.000E+00	.000E+00	.000E+00	.000E+00
CHROMIUM	.000E+00	.490E-02	.567E-02	.106E-01
COBALT	.000E+00	.490E-02	.745E-03	.564E-02
COPPER	.179E-03	.100E+00	.229E+00	.337E+00
FLUORINE	.000E+00	.000E+00	.516E-01	.516E-01
GALLIUM	.000E+00	.490E-03	.573E-03	.106E-02
GERMANIUM	< .596E-05	.000E+00	< .573E-04	< .632E-04
GOLD	.000E+00	.000E+00	.000E+00	.000E+00
IODINE	.596E-05	.000E+00	.000E+00	.596E-05
IRON	.000E+00	.930E+00	.000E+00	.930E+00
LANTHANUM	.000E+00	.000E+00	.000E+00	.000E+00
LEAD	.495E-03	.685E-02	.000E+00	.735E-02
LITHIUM	.000E+00	.979E-03	.172E-03	.115E-02
MAGNESIUM	.000E+00	.000E+00	.000E+00	.000E+00
MANGANESE	.179E-04	.000E+00	.115E-02	.116E-02
MERCURY	< .596E-04	.000E+00	.000E+00	< .596E-04
MOLYBDENUM	.239E-04	.245E-02	.000E+00	.247E-02
NEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00
NICKEL	.000E+00	U .000E+00	.344E-02	.344E-02
NIOBIUM	.000E+00	.000E+00	.115E-03	.115E-03
PHOSPHORUS	.119E-03	.392E-01	.573E-02	.450E-01
POTASSIUM	.179E-02	.588E-01	> .544E+00	> .605E+00
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	0 .000E+00	.000E+00
SAMARIUM	.596E-05	.000E+00	.000E+00	.596E-05
SCANDIUM	.000E+00	.000E+00	< .115E-03	< .115E-03
SELENIUM	.000E+00	.000E+00	.229E-01	.229E-01
SILICON	U .000E+00	U .000E+00	.516E+00	.516E+00
SILVER	.000E+00	< .490E-03	.115E-02	.115E-02<X<.164E-02
SODIUM	U .000E+00	.000E+00	> .544E+00	> .544E+00
STRONTIUM	.239E-03	.979E-03	.516E-03	.173E-02
SULFUR	.716E-02	.637E-01	> .561E+00	> .632E+00
TANTALUM	.000E+00	< .196E-02	.000E+00	< .196E-02

DIESEL NOX CONTROL
LOW NOX

MASS/HEAT INPUT
NG/J

ELEMENT	FILTER	XAD	IMPINGER 1+ OMC	EXHAUST
TELLURIUM	.000E+00	.000E+00	.115E-03	.115E-03
THORIUM	.000E+00	.000E+00	.000E+00	.000E+00
TIN	.119E-04	.000E+00	.458E-02	.459E-02
TITANIUM	.000E+00	.000E+00	.573E-03	.573E-03
TUNGSTEN	.000E+00	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.000E+00	.000E+00	.573E-04	.573E-04
YTTRIUM	.000E+00	.000E+00	.573E-04	.573E-04
ZINC	.358E-03	.539E-01	.170E+00	.224E+00
ZIRCONIUM	.596E-04	.000E+00	.344E-03	.403E-03

DIESEL NOX CONTROL
LOW NOX

MASS/HEAT INPUT
NG/J

ELEMENT	DIESEL FUEL	LUBE OIL	EXHAUST
ALUMINUM	.114E+00	.161E-01	.979E-02
ANTIMONY	.160E-02	.460E-03	.401E-03<X<.407E-03
ARSENIC	.000E+00	.230E-01	.596E-05<X<.632E-04
BARIUM	.684E-02	.115E+01	.153E-01
BERYLLIUM	.000E+00	< .230E-03	.000E+00
BISMUTH	.000E+00	.000E+00	< .596E-05
BORON	< .228E-03	< .230E-03	.490E-03
BROMINE	.182E-02	.161E-01	.974E-03
CADMIUM	.000E+00	.161E-02	.344E-03<X<.350E-03
CALCIUM	.433E+00	> .230E+01	.000E+00
CERIUM	.456E-03	.000E+00	.000E+00
CESIUM	.000E+00	.230E-03	< .573E-04
CHLORINE	.684E-02	.122E+01	.000E+00
CHROMIUM	.228E-02	.161E+00	.106E-01
COBALT	.912E-03	.161E-01	.564E-02
COPPER	.456E-02	.115E+00	.337E+00
FLUORINE	.684E-01	.460E-02	.516E-01
GALLIUM	.000E+00	.115E-02	.106E-02
GERMANIUM	.000E+00	.000E+00	< .632E-04
GOLD	.000E+00	.000E+00	.000E+00
IODINE	.000E+00	.000E+00	.596E-05
IRON	.912E-03	.196E+01	.930E+00
LANTHANUM	.456E-03	.690E-03	.000E+00
LEAD	.684E-02	.230E-01	.735E-02
LITHIUM	.912E-03	.161E-02	.115E-02
MAGNESIUM	.228E-01	.690E-01	.000E+00
MANGANESE	.114E-02	.115E-01	.116E-02
MERCURY	.000E+00	.000E+00	< .596E-04
MOLYBDENUM	.456E-02	.920E-02	.247E-02
NEODYMIUM	.000E+00	.000E+00	.000E+00
NICKEL	.912E-02	.460E-01	.344E-02
NIOBIUM	.000E+00	.690E+00	.115E-03
PHOSPHORUS	.114E-01	.138E+00	.450E-01
POTASSIUM	.132E+01	> .230E+01	> .605E+00
PRASEODYMIUM	.000E+00	.000E+00	.000E+00
RUBIDIUM	.228E-03	.920E-03	.000E+00
SAMARIUM	.000E+00	.000E+00	.596E-05
SCANDIUM	< .228E-03	< .460E-03	< .115E-03
SELENIUM	.000E+00	.690E-02	.229E-01
SILICON	.114E+00	.221E+01	.516E+00
SILVER	.456E-02	.230E-03	.115E-02<X<.164E-02
SODIUM	.912E-01	> .230E+01	> .544E+00
STRONTIUM	.456E-02	.529E+00	.173E-02
SULFUR	.449E+02	.221E+03	> .632E+00
TANTALUM	.000E+00	.000E+00	< .196E-02

DIESEL NOX CONTROL
LOW NOX

MASS/HEAT INPUT
NG/J

ELEMENT	DIESEL FUEL	LUBE OIL	EXHAUST
TELLURIUM	.000E+00	.000E+00	.115E-03
THORIUM	.000E+00	.000E+00	.000E+00
TIN	.000E+00	.460E-02	.459E-02
TITANIUM	.456E-01	.161E+00	.573E-03
TUNGSTEN	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00
VANADIUM	.456E-03	.920E-03	.573E-04
YTTRIUM	.000E+00	.000E+00	.573E-04
ZINC	.137E-01	.414E+00	.224E+00
ZIRCONIUM	.000E+00	.000E+00	.403E-03

DIESEL NOX CONTROL
LOW NOX

MASS FLOW MCG/SEC

ELEMENT	FILTER	XAD	IMPINGER 1+ OMC	EXHAUST
ALUMINUM	U .000E+00	.435E+02	U .000E+00	.435E+02
ANTIMONY	< .265E-01	.000E+00	.178E+01	.178E+01<X<.181E+01
ARSENIC	.265E-01	.000E+00	< .254E+00	.265E-01<X<.281E+00
BARIUM	.000E+00	.653E+02	.254E+01	.678E+02
BERYLLIUM	.000E+00	.000E+00	.000E+00	.000E+00
BISMUTH	< .265E-01	.000E+00	.000E+00	< .265E-01
BORON	.000E+00	.218E+01	.000E+00	.218E+01
BROMINE	.000E+00	.000E+00	.433E+01	.433E+01
CADMIUM	< .265E-01	.000E+00	.153E+01	.153E+01<X<.155E+01
CALCIUM	U .000E+00	.000E+00	.000E+00	.000E+00
CERIUM	.000E+00	.000E+00	.000E+00	.000E+00
CESIUM	.000E+00	.000E+00	< .254E+00	< .254E+00
CHLORINE	.000E+00	.000E+00	.000E+00	.000E+00
CHROMIUM	.000E+00	.218E+02	.252E+02	.469E+02
COBALT	.000E+00	.218E+02	.331E+01	.251E+02
COPPER	.795E+00	.479E+03	.102E+04	.150E+04
FLUORINE	.000E+00	.000E+00	.229E+03	.229E+03
GALLIUM	.000E+00	.218E+01	.254E+01	.472E+01
GERMANIUM	< .265E-01	.000E+00	< .254E+00	< .281E+00
GOLD	.000E+00	.000E+00	.000E+00	.000E+00
IODINE	.265E-01	.000E+00	.000E+00	.265E-01
IRON	.000E+00	.413E+04	.000E+00	.413E+04
LANTHANUM	.000E+00	.000E+00	.000E+00	.000E+00
LEAD	.220E+01	.305E+02	.000E+00	.327E+02
LITHIUM	.000E+00	.435E+01	.763E+00	.511E+01
MAGNESIUM	.000E+00	.000E+00	.000E+00	.000E+00
MANGANESE	.795E-01	.000E+00	.509E+01	.517E+01
MERCURY	< .265E+00	.000E+00	.000E+00	< .265E+00
MOLYBDENUM	.106E+00	.109E+02	.000E+00	.110E+02
NEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00
NICKEL	.000E+00	U .000E+00	.153E+02	.153E+02
NIOBIUM	.000E+00	.000E+00	.509E+00	.509E+00
PHOSPHORUS	.530E+00	.174E+03	.254E+02	.200E+03
POTASSIUM	.795E+01	.261E+03	> .242E+04	> .269E+04
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	0 .000E+00	.000E+00
SAMARIUM	.265E-01	.000E+00	.000E+00	.265E-01
SCANDIUM	.000E+00	.000E+00	< .509E+00	< .509E+00
SELENIUM	.000E+00	.000E+00	.102E+03	.102E+03
SILICON	U .000E+00	U .000E+00	.229E+04	.229E+04
SILVER	.000E+00	< .218E+01	.509E+01	.509E+01<X<.726E+01
SODIUM	U .000E+00	.000E+00	> .242E+04	> .242E+04
STRONTIUM	.106E+01	.435E+01	.229E+01	.770E+01
SULFUR	.318E+02	.283E+03	> .249E+04	> .281E+04
TANTALUM	.000E+00	< .870E+01	.000E+00	< .870E+01

DIESEL NOX CONTROL
Low NOX

MASS FLOW ELEMENT	MCG/SEC FILTER	XAD	IMPINGER 1+ OMC	EXHAUST
TELLURIUM	.000E+00	.000E+00	.509E+00	.509E+00
THORIUM	.000E+00	.000E+00	.000E+00	.000E+00
TIN	.530E-01	.000E+00	.204E+02	.204E+02
TITANIUM	.000E+00	.000E+00	.254E+01	.254E+01
TUNGSTEN	.000E+00	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.000E+00	.000E+00	.254E+00	.254E+00
YTTRIUM	.000E+00	.000E+00	.254E+00	.254E+00
ZINC	.159E+01	.239E+03	.756E+03	.997E+03
ZIRCONIUM	.255E+00	.000E+00	.153E+01	.179E+01

DIESEL NOX CONTROL

LOW NOX

MASS FLOW MCG/SEC

ELEMENT	DIESEL FUEL	LUBE OIL	EXHAUST
ALUMINUM	.505E+03	.247E+00	.435E+02
ANTIMONY	.707E+01	.706E-02	.178E+01<X<.181E+01
ARSENIC	.000E+00	.353E+00	.265E-01<X<.281E+00
BARIUM	.303E+02	.176E+02	.678E+02
BERYLLIUM	.000E+00	< .353E-02	.000E+00
BISMUTH	.000E+00	.000E+00	< .265E-01
BORON	< .101E+01	< .353E-02	.218E+01
BROMINE	.808E+01	.247E+00	.433E+01
CADMIUM	.000E+00	.247E-01	.153E+01<X<.155E+01
CALCIUM	.192E+04	> .353E+02	.000E+00
CERIUM	.202E+01	.000E+00	.000E+00
CESIUM	.000E+00	.353E-02	< .254E+00
CHLORINE	.303E+02	.187E+02	.000E+00
CHROMIUM	.101E+02	.247E+01	.469E+02
COBALT	.404E+01	.247E+00	.251E+02
COPPER	.202E+02	.176E+01	.150E+04
FLUORINE	.303E+03	.706E-01	.229E+03
GALLIUM	.000E+00	.176E-01	.472E+01
GERMANIUM	.000E+00	.000E+00	< .281E+00
GOLD	.000E+00	.000E+00	.000E+00
IODINE	.000E+00	.000E+00	.265E-01
IRON	.404E+01	.300E+02	.413E+04
LANTHANUM	.202E+01	.106E-01	.000E+00
LEAD	.303E+02	.353E+00	.327E+02
LITHIUM	.404E+01	.247E-01	.511E+01
MAGNESIUM	.101E+03	.106E+01	.000E+00
MANGANESE	.505E+01	.176E+00	.517E+01
MERCURY	.000E+00	.000E+00	< .265E+00
MOLYBDENUM	.202E+02	.141E+00	.110E+02
NEODYMIUM	.000E+00	.000E+00	.000E+00
NICKEL	.404E+02	.706E+00	.153E+02
NIOBIUM	.000E+00	.000E+00	.509E+00
PHOSPHORUS	.505E+02	.212E+01	.200E+03
POTASSIUM	.586E+04	> .353E+02	> .269E+04
PRASEODYMIUM	.000E+00	.000E+00	.000E+00
RUBIDIUM	.101E+01	.141E-01	.000E+00
SAMARIUM	.000E+00	.000E+00	.265E-01
SCANDIUM	< .101E+01	< .706E-02	< .509E+00
SELENIUM	.000E+00	.106E+00	.102E+03
SILICON	.505E+03	.339E+02	.229E+04
SILVER	.202E+02	.353E-02	.509E+01<X<.726E+01
SODIUM	.404E+03	> .353E+02	> .242E+04
STRONTIUM	.202E+02	.812E+01	.770E+01
SULFUR	.199E+06	.339E+04	> .281E+04
TANTALUM	.000E+00	.000E+00	< .678E+01

DIESEL NOX CONTROL
LOW NOX

MASS FLOW MCG/SEC

ELEMENT	DIESEL FUEL	LUBE OIL	EXHAUST
TELLURIUM	.000E+00	.000E+00	.509E+00
THORIUM	.000E+00	.000E+00	.000E+00
TIN	.000E+00	.706E-01	.204E+02
TITANIUM	.202E+03	.247E+01	.254E+01
TUNGSTEN	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00
VANADIUM	.202E+01	.141E-01	.254E+00
YTTRIUM	.000E+00	.000E+00	.254E+00
ZINC	.606E+02	.635E+01	.997E+03
ZIRCONIUM	.000E+00	.000E+00	.179E+01

DIESEL NOX CONTROL
Low NOX

ENGINE MASS-BALANCE

INPUT = DIESEL FUEL + LUBE OIL

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OIL + EXHAUST)
ALUMINUM	.505E+03	.435E+02	.861E-01
ANTIMONY	.708E+01	.178E+01<X<.181E+01	.252E+00<X<.255E+00
ARSENIC	.353E+00	.265E-01<X<.281E+00	.751E-01<X<.796E+00
BARIUM	.480E+02	.678E+02	.141E+01
BERYLLIUM	X<.353E-02		.000E+00
BISMUTH		X<.265E-01	•
BORON	X<.101E+01	.218E+01	.215E+01 <X
BROMINE	.833E+01	.433E+01	.520E+00
CADMIUM	.247E-01	.153E+01<X<.155E+01	.618E+02<X<.629E+02
CALCIUM	.195E+04 <X		.000E+00
CERIUM	.202E+01		.000E+00
CESIUM	.353E-02	X<.254E+00	.000E+00<X<.721E+02
CHLORINE	.498E+02		.000E+00
CHROMIUM	.126E+02	.469E+02	.373E+01
COBALT	.429E+01	.251E+02	.585E+01
COPPER	.220E+02	.150E+04	.682E+02
FLUORINE	.303E+03	.229E+03	.756E+00
GALLIUM	.176E-01	.472E+01	.267E+03
GERMANIUM		X<.281E+00	•
GOLD			•
IODINE		.265E-01	•
IRON	.348E+02	.413E+04	.121E+03
LANTHANUM	.203E+01		.000E+00
LEAD	.307E+02	.327E+02	.107E+01
LITHIUM	.486E+01	.511E+01	.126E+01
MAGNESIUM	.102E+03		.000E+00
MANGANESE	.523E+01	.517E+01	.989E+00
MERCURY		X<.265E+00	•
MOLYBDENUM	.203E+02	.118E+02	.546E+00
NEODYMIUM			•
NICKEL	.411E+02	.153E+02	.371E+00
NIOBIUM		.509E+00	•
PHOSPHORUS	.526E+02	.200E+03	.380E+01
POTASSIUM	.589E+04 <X	.269E+04 <X	•
PRASEODYMIUM			•
RUBIDIUM	.102E+01		.000E+00
SAMARIUM		.265E-01	•
SCANDIUM	X<.102E+01	X<.509E+00	•
SELENIUM	.106E+00	.102E+03	.961E+03
SILICON	.539E+03	.229E+04	.425E+01
SILVER	.202E+02	.509E+01<X<.726E+01	.252E+00<X<.360E+00
SODIUM	.439E+03 <X	.242E+04 <X	•
STRONTIUM	.283E+02	.770E+01	.272E+00
SULFUR	.202E+06	.281E+04 <X	.139E-01 <X
TANTALUM		X<.870E+01	•

DIESEL NOX CONTROL
LOW NOX

ENGINE MASS-BALANCE

ELEMENT	INPUT = DIESEL FUEL + LUBE OIL TOTAL IN	TOTAL OUT	OUTPUT = EXHAUST MASS BALANCE (OUT/IN)
TELLURIUM		.589E+00	•
THORIUM			•
TIN	.706E-01	.284E+02	.289E+03
TITANIUM	.284E+03	.254E+01	.124E-01
TUNGSTEN			•
URANIUM			•
VANADIUM	.283E+01	.254E+00	.125E+00
YTTRIUM		.254E+00	•
ZINC	.670E+02	.997E+03	.149E+02
ZIRCONIUM		.179E+01	•

APPENDIX C

CONVERSION UNITS AND SAMPLE CALCULATIONS

Conversion Units

To obtain	Multiply	By
Watt (W)	Bhp	746
Joules (output)	Bhp-hr	2.68×10^6
Joules	Btu	1,055
g	lb	454
g/kW-hr	lb/Bhp-hr	609
Pa	psi	6,895
l/s	gpm	6.31×10^{-2}
kg/s	lbs/min	7.58×10^{-3}
ng/J (input)	lb/10^6 Btu (input)	430
	g/Bhp-hr (output)	$3.72 \times 10^2 \varepsilon$

where ε = engine efficiency

K = (°F+ 460)/1.8

Sample Calculations

a) $$BSFC = \frac{W_f\ (60)}{Bhp}$$

b) $$CID/cyl = \pi \frac{(\text{cylinder bore diameter})^2}{4} \times \text{stroke} \times 2$$

c) $$BMEP = \frac{Bhp\ (33000)\ 12}{\frac{CID}{cyl}\ (\text{number of cylinders})\ \frac{RPM}{2}}$$

d) BS(a) dry basis = 4.54×10^{-6} x MW (a) x NTD' x ppm (dry) x BSFC

where:

NTD' = Moles of dry exhaust products/100 lbs of fuel

e) Correction of NO_X/NO to standard atmospheric conditions of 10.71 g H_2O/kg air (75 grain/lb air) humidity and 302K (85°F) ambient temperature:

$$NO_X \text{ corrected} = NO_X \times k_H \times k_T$$

Where:

$$k_H = 0.844 + 0.151\ \frac{H}{100} + 0.75\ \left(\frac{H}{100}\right)^2$$

$$k_T = 1 - (T - 85)\ (0.0135)$$

and:

H = Observed humidity in grains H_2O/pound of dry air

T = Observed inlet air temperature in °F

APPENDIX D

GLOSSARY OF TERMS USED

AAS	Atomic Absorption Spectroscopy
A/F	Air-to-fuel ratio - weight basis
Bhp	Brake horsepower
BMEP	Brake mean effective pressure
BMV	Before minimum (cylinder) volume
BS(a)	Brake specific emissions - grams of pollutant (a) produced by the engine in developing 1 Bhp-hr
BSFC	Brake specific fuel consumption in pounds of fuel per Bhp-hr
CID/cyl	Cubic inches piston displacement per cylinder. Since opposed piston engine has two piston per cylinder the total CID/cyl is twice the displacement of each piston
DEMA	Diesel Engine Manufacturers Association
DSCM	Dry standard cubic meter
FID	Flame ionization detector
GC	Gas chromatography
GC/MS	Gas chromatography/mass spectroscopy
MW(a)	Molecular weight of pollutant (a)
NDIR	Nondispersive infrared
POM	Polycyclic organic matter
RPM	Revolutions per minute - engine speed
SASS	Source assessment sampling system

SSMS	Spark source mass spectroscopy
TDS	Total discharge severity
W_f	Weight of fuel flow, pounds per hour